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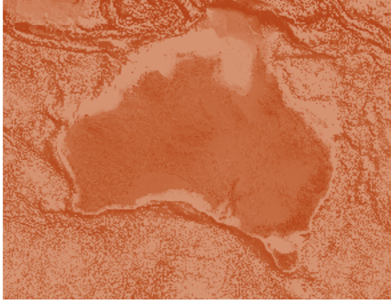

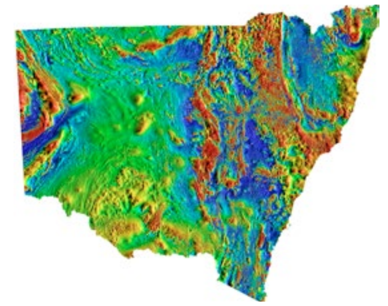

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NSW GOVERNMENT | Trade & Investment Resources & Energy

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REPORT GS2013/1837

Emma-Kate Chisholm[1], Phillip Blevin[2], Peter Downes[2] and Carol Simpson[2]

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Contents

Executive Summary

This Record presents new zircon U–Pb geochronological data, obtained using a Sensitive High Resolution Ion Micro Probe (SHRIMP), for five samples of plutonic and volcanic rocks from the central Lachlan Orogen and the Thomson Orogen, New South Wales. The work was carried out under the auspices of the National Geoscience Accord, as a component of the collaborative Geochronology Project between the Geological Survey of New South Wales (GSNSW) and Geoscience Australia (GA) during the reporting period July 2011 to June 2012.

The five samples were selected with the aim of refining the regional chronology of magmatism to better inform geological models in the Nymagee–Louth region. Four samples were analysed from the Nymagee region of the central Lachlan Orogen (comprising two from the Winduck Shelf, one from the Mount Hope Trough, and one from the Cobar Basin), and one from the Louth region of the Thomson Orogen, New South Wales.

Central Lachlan Orogen

Four samples were sourced from the area to the west of Nymagee in the central Lachlan Orogen with the aim of refining the regional chronology of magmatism.

In the Winduck Shelf area, a sample of the Thule Granite obtained from drillcore at the 'Wontawinta Dome' near the Wontawinta silver mine site yielded a magmatic crystallisation age of 425.7 ± 2.4 Ma (all uncertainties are quoted at the 95% confidence level). This Late Silurian age suggests that previous K-Ar ages obtained on the Thule granite (408 ± 6 Ma and 416 ± 6 Ma, both on muscovite, and 422 ± 6 Ma on biotite; Pogson and Hilyard, 1981) have been at least partially reset. Similarly, an unnamed granite intersected in a drillhole at the De Nardi Prospect in the Winduck Shelf yielded a mid-Late Silurian magmatic crystallisation age of 427.2 ± 3.1 Ma. This age is indistinguishable from that of the Thule Granite, as well as those of several Keotong Supersuite plutons previously dated on CARGELLIGO to the south (Black, 2005; Colquhoun et al., 2005; fully-capitalised names refer to map sheets in the 1:250 000 Topographic Series).

In the Mt Hope Trough, the S-type Mount Halfway Volcanics of the Mount Hope Group (Blevin and Jones, 2004), which are inferred to overlie the Thule Granite (Scheibner, 1987), yielded a Late Silurian magmatic crystallisation age of 422.8 ± 2.6 Ma.

An unnamed granite intersected in a drillhole at the R7 Prospect (Sandy Creek), in the western part of the Cobar Basin, yielded a magmatic crystallisation age of 422.8 ± 4.9 Ma, suggesting the granite is equivalent to the Mount Halfway Volcanics and the cordierite-biotite bearing S-type Early Devonian Gilgunnia Granite, the age of which was inferred due to an intrusive relationship with the volcanics of the Mount Hope Group and the lower Amphitheatre Group (MacRae, 1989). Geochemical analyses by Blevin and Jones (2004) show the Gilgunnia Granite is petrographically and chemically related to the Mount Halfway Volcanics. An unpublished U–Pb SHRIMP age 422.5 ± 3.6 Ma for the Gilgunnia Granite (sampled immediately to the south of the R7 Prospect) was determined by Richard Armstrong (PRISE – ANU, pers. comm.). The Gilgunnia Granite age is indistinguishable from the age of the unnamed granite at the R7 Prospect. Petrographic differences between the R7 Prospect intrusion and

the Gilgunnia Granite suggests that the R7 Prospect intrusion may be a felsic and fractionated variant. Of note is that the age of the unnamed granite at the R7 Prospect is older than the mapped host geology (Amphitheatre Group) indicating that stratigraphic correlations in the region need to be reviewed, particularly in units with poor fossil control (e.g. Sherwin, 2013).

Thomson Orogen

One sample was sourced from the Louth region of the Thomson Orogen to constrain local intrusive relationships in a broad region where little dating has been previously conducted. The 'Cuttaburra granite' is previously undescribed and its geochemical classification (S- versus I-type) is indeterminate. It yielded a magmatic crystallisation age of 428.3 ± 2.8 Ma, which is indistinguishable from several S-type Koetong Supersuite plutons previously dated to the south (Black, 2005; Colquhoun et al., 2005), and similar to the S-type Thule Granite in the Nymagee region (this volume). This age correlates closely with ages of S-type magmatism elsewhere, however lack of dating of granites more proximal to the granite at Cuttaburra precludes any assessment of the effect of regional age patterns.

1 Introduction

This Record presents new zircon U–Pb geochronological data, obtained using a Sensitive High Resolution Ion MicroProbe (SHRIMP) for four samples of plutonic and volcanic rocks from the Nymagee region of the central Lachlan Orogen, and one sample of a plutonic rock from the Thomson Orogen, New South Wales. The work was carried out under the auspices of the National Geoscience Accord, as a component of the collaborative Geochronology Project between the Geological Survey of New South Wales (GSNSW) and Geoscience Australia (GA) during the reporting period July 2011 to June 2012.

Of the five samples, four were analysed from the NYMAGEE 1:250 000 topographic map sheet (large and small capitals refer to map sheet names in the 1:250 000 and 1:100 000 Topographic Series respectively); one sample from MOUNT ALLEN (south-eastern NYMAGEE) and three from LACHLAN DOWNS (north-eastern NYMAGEE). The fifth sample was analysed from THOOLABOOL (south-western LOUTH). The results are summarised in Table 1.1 and sample locations shown in Figure 1.1.

Table 1.1 Summary of sample identifiers, locations, stratigraphic units and results (magmatic crystallisation age for five samples and associated 95% confidence limits) for the GSNSW–GA Geochronology Project 2011–2012 (Nymagee, central Lachlan Orogen and Louth, Thomson Orogen). Single quotes denote informal identifiers; n = number of analyses included in the weighted mean age.

GSNSW Site ID	GA SampleNo	MGA94 Zone	Easting	Northing	Stratigraphic Name	$^{206}Pb/^{238}U$ age (Ma)
MOUNT ALLEN 1:100 000 map sheet						
PB-11-NYM-15	2128512	55	393436	6401285	Mount Halfway Volcanics	422.8 ± 2.6 (n = 23)
LACHLAN DOWNS 1:100 000 map sheet						
PB-11-NYM-16	2128513	55	404874	6438153	R7 Prospect unnamed granite	422.8 ± 4.9 (n = 4)
PB-11-NYM-17	2128514	55	381799	6433401	Thule Granite	425.7 ± 2.4 (n = 28)
PB-11-NYM-18	2128515	55	387185	6457300	De Nardi Prospect unnamed granite	427.2 ± 3.1 (n = 13)
THOOLABOOL 1:100 000 map sheet						
PB-11-THOM-01	2128516	55	232923	6606450	'Cuttaburra granite'	428.3 ± 2.8 (n = 19)

This Record documents detailed results for each sample, encompassing sample location, geological context, petrography, zircon descriptions, an evaluation of the relevant analytical data, and a brief geochronological interpretation. The data and age interpretations are also available via GA's Geochron Delivery system (accessible at http://www.ga.gov.au/geochron-sapub-web/).

This Record does not attempt to present the new SHRIMP U–Pb results in the context of an exhaustive regional assessment, nor does it consider all of the relevant and available geological and geochronological information. Comprehensive geological interpretations stemming from this data will be documented elsewhere.

A comprehensive description of sample acquisition and processing procedures, preparation and analysis of the SHRIMP mount, and data reduction and presentation methods are included in the Appendix, along with analytical session-specific details of the calibration data collected on the reference $^{206}Pb/^{238}U$ and $^{207}Pb/^{206}Pb$ zircons. Session specific calibrations are summarised in Appendix Table A.1.

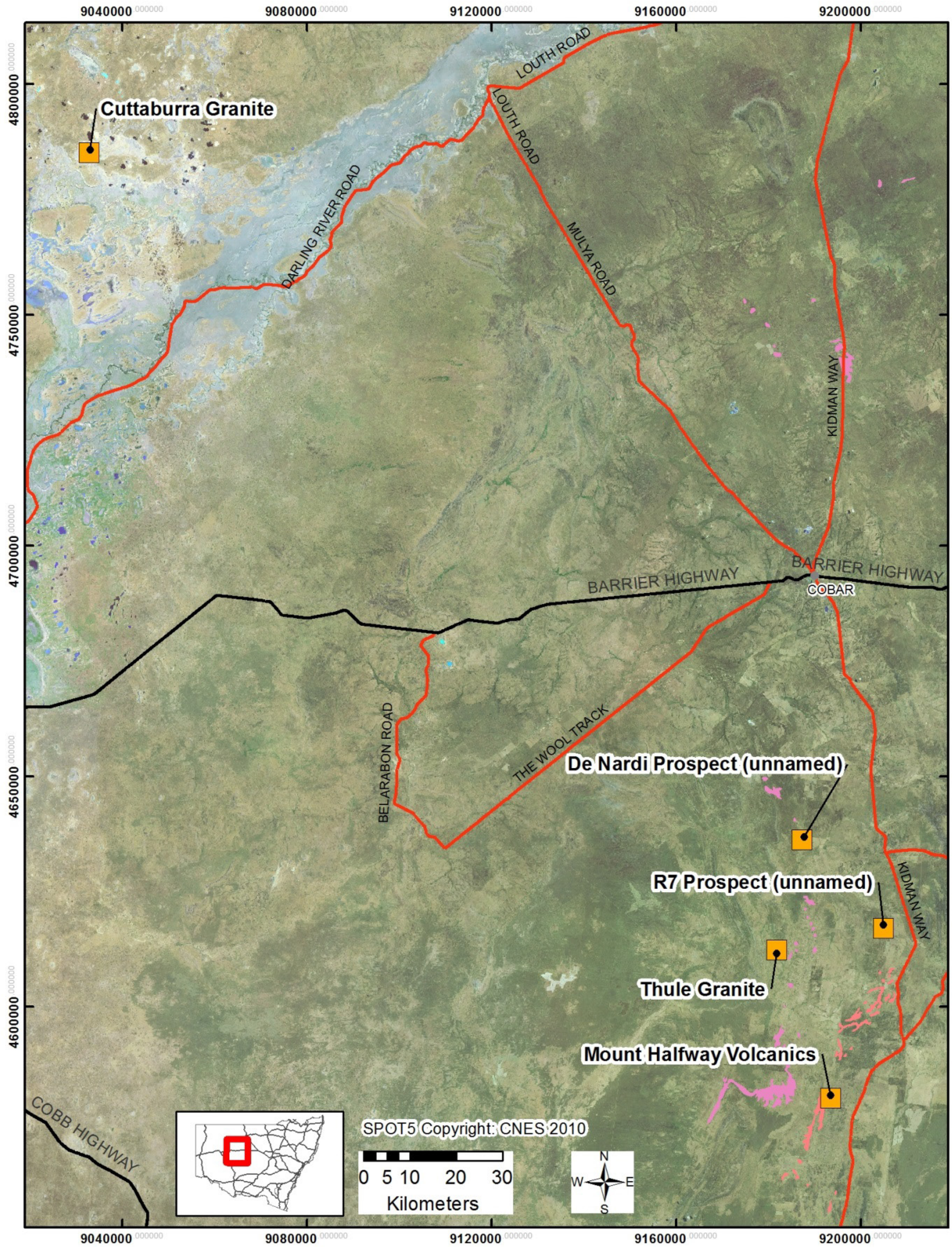


Figure 1.1 Map showing locations for the SHRIMP U–Pb geochronology samples presented in this Record. Pink polygons represent outcropping granites, orange squares represent locations of samples. Refer to Table 1.1 for sample identifiers and location coordinates.

2 Mount Halfway Volcanics

Table 2.1 Summary of results: Mount Halfway Volcanics (GSNSW: PB-11-NYM-15, GA: 2128512).

GA SampleNo	2128512
GSNSW SiteID	PB-11-NYM-15
Parent Unit	Mount Hope Group, Cobar Supergroup
Stratigraphic Unit	Mount Halfway Volcanics
Informal Identifier	The Peaks Porphyry (MacRae, 1987, 1989)
Lithology	Rhyolite
Province	Mount Hope Trough, central Lachlan Orogen
1:250 000 Sheet	NYMAGEE (SI/55-2)
1:100 000 Sheet	MOUNT ALLEN (8032)
Location (GDA94)	32.520646°S, 145.865379°E
Location (MGA94)	Zone 55; 393436 mE, 6401285 mN
Analytical Session No	120014; 13–16 February 2012 (see Appendix Table A1.1 for parameters derived from concurrent measurements of $^{206}Pb/^{238}U$ and $^{207}Pb/^{206}Pb$ reference zircons)
Interpreted Age	422.8 ± 2.6 Ma (n = 23)
Geological Attribution	Magmatic crystallisation age
Isotopic Ratio used	$^{206}Pb/^{238}U$ (^{204}Pb-corrected)

2.1 Sampling Details and Geological Relationships

The sample of the Mount Halfway Volcanics (Barron et al., 1982) comprises a 4.4 kg segment of drill core from hole ZFXDD1 (interval 408.9 m to base of hole) consisting of a coherent quartz feldspar phenocryst bearing volcaniclastic rhyolite.

The Mount Halfway Volcanics (Figure 2.1) is the most widespread formation of the Mount Hope Group (MacRae, 1987, 1989; Scheibner 1987), extending ~80 km from the southern region of MOUNT ALLEN, through the north to the northeast onto LACHLAN DOWNS and NYMAGEE, with a maximum thickness of ~2 km (Barron et al., 1982) and younging to the south (MacRae, 1989). MacRae (1987, 1989) referred to the Mount Halfway Volcanics as 'The Peaks Porphyry'.

On MOUNT ALLEN, the Mount Halfway Volcanics conformably overlie the Coando Volcanics and are conformably overlain by the Goona Volcanics (Barron et al., 1982). On LACHLAN DOWNS, the Mount Halfway Volcanics interfingers with the Amphitheatre Group, which contains Lochkovian trilobite *Encrinurus sp.* and *Molongia capricornae* brachiopods, and both units are intruded by the Early Devonian Gilgunnia Granite (422.5 ± 3.6 Ma; unpubl., PRISE – ANU, pers. comm.), a high level pluton that is inferred to be co-magmatic with the Mount Halfway Volcanics (MacRae, 1989).

The Mount Hope Group is inferred to overlie the Thule Granite (425.7 ± 2.4 Ma; this volume) although contacts are not exposed (Scheibner, 1987).

The sample was sourced from the volcanic and sedimentary package of the Mount Halfway Volcanics with the aim of obtaining an age to constrain the time range of volcanism in the Mount Hope Group of the western Cobar Basin sequence.

Figure 2.1 Representative photograph of the Mount Halfway Volcanics in outcrop. Image provided by the Geological Survey of New South Wales.

2.2 Petrography

The sample is a weakly foliated, medium-grained, moderately crystal-rich (~20–25% phenocrysts), plagioclase- and quartz-phyric coherent rhyolite (Figure 2.2). Subhedral plagioclase phenocrysts are up to 3 mm in size, lightly calcite- and sericite-altered and tend to cluster in aggregates up to 10 mm in size. The majority of the embayed quartz phenocrysts have undergone in situ shattering and some disaggregation. The rhyolite lacks obvious ferromagnesian phenocrysts but does contain 2–3% usually lenticular patches that consist of very fine white mica that has been overprinted by fine-grained decussate secondary (?contact metamorphic) biotite and minor epidote and opaques. Based on observation of less altered samples of Mount Halfway Volcanics, these lenses of secondary minerals have probably replaced ferromagnesian minerals such as pyroxene or possibly fayalite. The rock contains conspicuous accessory zircon and apatite. The groundmass is variably finely microcrystalline and finely sericite-altered but retains a clear perlitic texture that is indicative of hydration of an originally glassy rock.

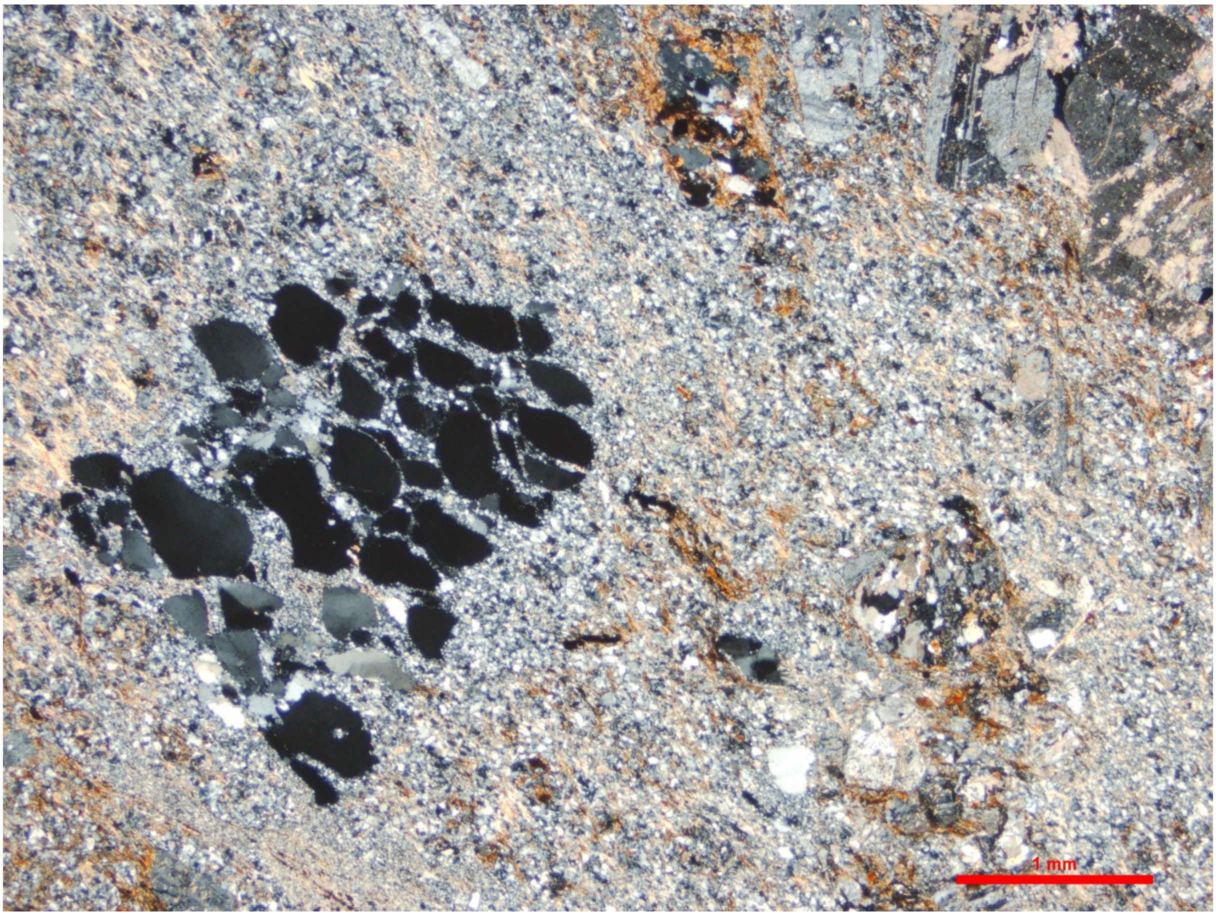


Figure 2.2 Representative photomicrograph of the Mount Halfway Volcanics (GSNSW: PB-11-NYM-15, GA: 2128512) taken under cross-polarised light. Altered coherent perlitic rhyolite with a carbonate-altered plagioclase phenocryst (top right) and smaller plagioclase (right of centre), and in situ shattered quartz phenocryst (left). The perlitic nature of the groundmass is not clear in this view as it is obscured by the abundance of secondary sericite and stringers of brown biotite. Scale bar is 1 mm. Image provided by the Geological Survey of New South Wales.

2.3 Zircon Description

Zircons are predominantly euhedral prismatic grains with subordinate subhedral grains. Long axes are 40–200 µm and length to width varies from 1:1 to 4:1 (Figure 2.3).

In transmitted light (Figure 2.3), euhedral zircons are predominantly transparent and colourless. Subhedral grains are colourless, transparent to translucent and represent approximately 20% of the population. Cracks are present in approximately 20% of grains, the majority in the subhedral population. Rare inclusions are present.

Cathodoluminescence (CL) images reveal a range of CL emission responses (Figure 2.3). Diffuse to broad to high contrast fine oscillatory zoning is seen in the euhedral population. Cores are present throughout the population and show crosscutting textures, convolute zoning, and diffuse low intensity recrystallisation textures.

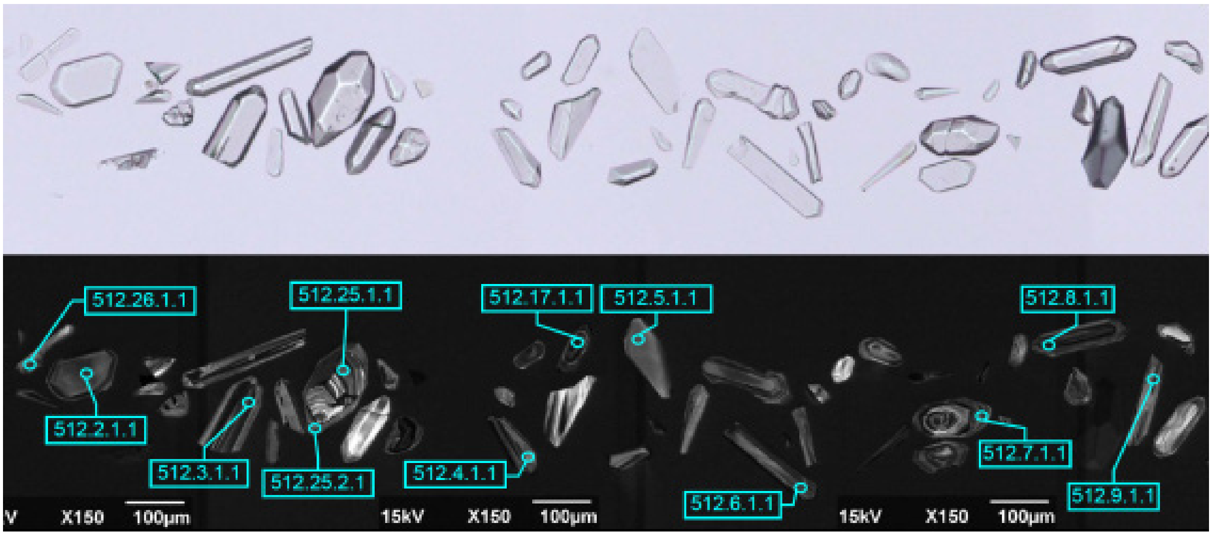


Figure 2.3 Representative zircons from the Mount Halfway Volcanics (GSNSW: PB-11-NYM-15, GA: 2128512). Transmitted light image is shown in the upper half and cathodoluminescence image in the lower half. SHRIMP analysis sites are labelled with sample (prefix 2128- not annotated), grain, spot and replicate number. Scale bar is 100 µm.

2.4 U–Pb Isotopic Results

Thirty-three analyses were obtained from 28 zircons; results are presented in Figure 2.4 and Table 2.2. The analysed zircons are characterised by a low to moderate range of ^{238}U contents (99–600 ppm, median 253 ppm), with variable $^{232}Th/^{238}U$ (0.02–1.10, median 0.28).

Three analyses (512.5.1.1, 512.24.1.1 and 512.26.1.1) were adversely affected by instrument instability during the acquisition of data and are not considered further.

The remaining 30 analyses are characterised by low $^{206}Pb_c$ (maximum 0.33%, median 0.02%) and can be divided into three groups:

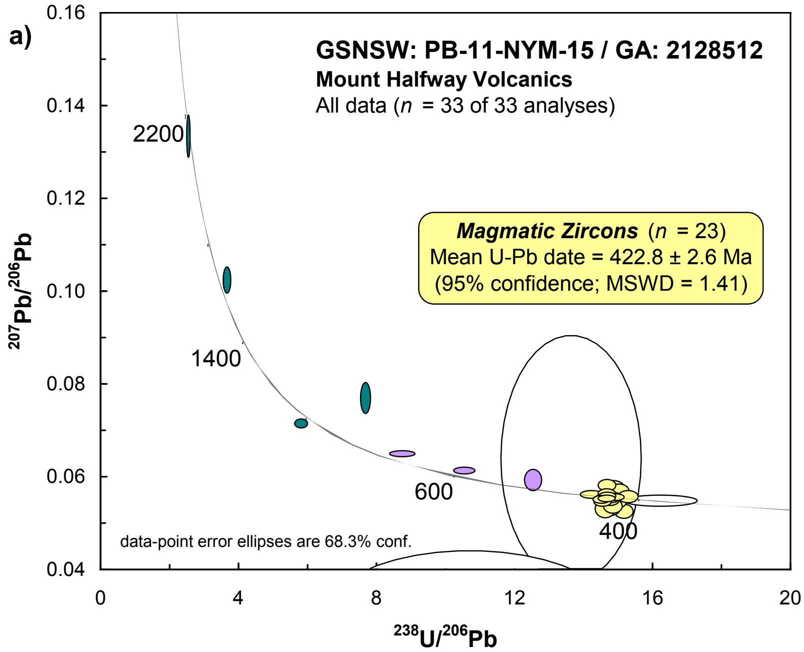
- Group 1: 23 analyses (Figure 2.4, yellow fill) of euhedral zircons with oscillatory zoning, with individual $^{206}Pb/^{238}U$ ages between ~439 Ma and ~409 Ma. The analyses combine to produce a weighted mean $^{206}Pb/^{238}U$ age of 422.8 ± 2.6 Ma (95% confidence, MSWD = 1.41, probability of equivalence = 0.09).
- Group 2: three analyses (Figure 2.4, purple fill) with individual $^{206}Pb/^{238}U$ ages between ~702 Ma and ~496 Ma that are significantly older than the analyses in Group 1 and are visible as cores in CL images (Figure 2.3).
- Group 3: four analyses (Figure 2.4, green fill) with individual $^{207}Pb/^{206}Pb$ ages between ~2146 Ma and ~969 Ma that are significantly older than the analyses in Group 1 and are visible as cores in CL images (Figure 2.3).

2.5 Geochronological Interpretation

The weighted mean $^{206}Pb/^{238}U$ age of 422.8 ± 2.6 Ma for the 23 analyses in Group 1 is interpreted to be the magmatic crystallisation age of the Mount Halfway Volcanics.

The three analyses in Group 2 are interpreted as inheritance of Silurian to Paleoproterozoic age, and the four analyses in Group 3 are interpreted as inheritance of Pre-Neoproterozoic age.

The age of 422.8 ± 2.6 Ma for the Mount Halfway Volcanics is indistinguishable from the unpublished U–Pb SHRIMP age 422.5 ± 3.6 Ma obtained by Richard Armstrong for the Gilgunnia Granite (PRISE – ANU, pers. comm.). The geochemical analyses by Blevin and Jones (2004) show the Gilgunnia Granite is petrographically and chemically related to the Mount Halfway Volcanics, and with the new age, confirms the co-magmatic relationship between the two units proposed by MacRae (1989).



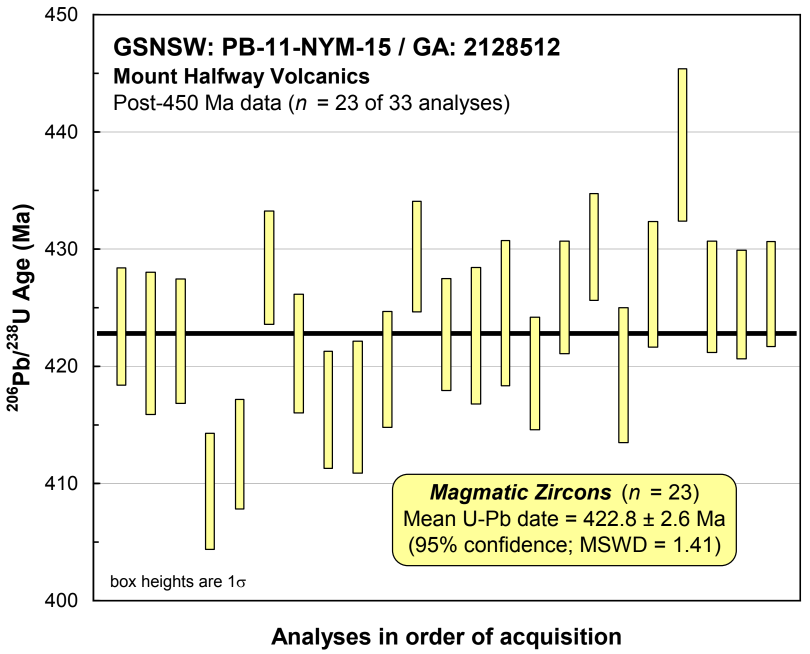


Figure 2.4 SHRIMP U–Pb data for zircons from the Mount Halfway Volcanics (GSNSW: PB-11-NYM-15, GA: 2128512). Yellow fill denotes magmatic zircons, purple fill denotes Neoproterozoic–Cambrian inheritance, green fill denotes pre-Neoproterozoic inheritance, and unfilled ellipses denote analyses affected by instrument instability. (a) Tera-Wasserberg Concordia diagram; (b) post-450 Ma and pre-400 Ma $^{206}Pb/^{238}U$ *ages in order of acquisition; heavy black line represents the weighted mean* $^{206}Pb/^{238}U$ *age of the magmatic population.*

Table 2.2 SHRIMP U–Pb isotopic data for zircons from the Mount Halfway Volcanics (GSNSW: PB-11-NYM-15, GA: 2128512). Ages are $^{206}Pb/^{238}U$ unless otherwise indicated.

Sample. Grain. Spot. Replicate	$^{206}Pb_c$ (%)	U (ppm)	Th (ppm)	$^{232}Th/^{238}U$	$^{238}U/^{206}Pb$	±1σ (%)	$^{207}Pb/^{206}Pb$	±1σ (%)	Disc. (%)	Age (Ma)	±1σ (Ma)
Group 1: Magmatic zircons (n = 23)											
2128512.4.1.1	0.04	179	76	0.44	15.256	1.2	0.05559	1.6	6	409.3	4.9
2128512.6.1.1	0.33	246	45	0.19	15.134	1.2	0.05240	1.9	-37	412.5	4.7
2128512.12.1.1	-0.15	168	84	0.52	14.992	1.2	0.05686	1.8	15	416.3	5.0
2128512.13.1.1	0.06	99	68	0.71	14.983	1.4	0.05563	2.1	5	416.5	5.6
2128512.25.2.1	0.20	274	74	0.28	14.883	1.4	0.05438	1.6	-9	419.2	5.8
2128512.22.1.1	-0.05	227	52	0.24	14.878	1.2	0.05660	2.7	12	419.4	4.8
2128512.15.1.1	-0.01	547	74	0.14	14.866	1.2	0.05548	0.9	3	419.7	5.0
2128512.11.1.1	0.17	169	29	0.17	14.815	1.2	0.05359	1.9	-20	421.1	5.1
2128512.2.1.1	-0.18	299	23	0.08	14.784	1.5	0.05791	1.3	20	421.9	6.1
2128512.3.1.1	-0.05	350	159	0.47	14.777	1.3	0.05566	1.1	4	422.1	5.3
2128512.19.1.1	-0.19	248	31	0.13	14.760	1.4	0.05638	1.5	10	422.6	5.8
2128512.18.1.1	0.07	259	169	0.68	14.757	1.2	0.05537	1.3	1	422.7	4.8
2128512.1.1.1	-0.09	185	87	0.49	14.732	1.2	0.05494	1.6	-3	423.4	5.0
2128512.20.1.1	0.24	201	58	0.30	14.691	1.5	0.05287	1.9	-32	424.5	6.2
2128512.14.2.1	-0.02	384	87	0.23	14.664	1.1	0.05569	1.0	3	425.3	4.6
2128512.21.1.1	-0.19	253	63	0.26	14.643	1.2	0.05805	1.5	21	425.9	4.8
2128512.7.1.1	-0.06	300	45	0.16	14.641	1.2	0.05621	1.2	8	425.9	4.8
2128512.28.1.1	0.03	600	81	0.14	14.633	1.1	0.05518	0.9	-2	426.2	4.5
2128512.12.2.1	0.33	140	91	0.67	14.603	1.3	0.05295	2.5	-32	427.0	5.4
2128512.9.1.1	0.00	257	65	0.26	14.553	1.2	0.05511	1.1	-3	428.4	4.8
2128512.16.1.1	0.04	335	193	0.59	14.520	1.1	0.05446	1.1	-10	429.3	4.7
2128512.23.1.1	0.09	482	227	0.49	14.492	1.1	0.05503	1.0	-4	430.2	4.6
2128512.17.1.1	-0.04	474	167	0.36	14.194	1.5	0.05607	0.9	4	438.9	6.5
Group 2: Cambrian–Neoproterozoic inheritance (n = 3)											
2128512.22.2.1	-0.47	111	118	1.10	12.500	1.4	0.05922	2.6	14	496.1	6.5
2128512.10.1.1	0.01	503	8	0.02	10.505	2.0	0.06121	0.8	10	586.2	11.0
2128512.8.1.1	0.05	460	138	0.31	8.699	2.8	0.06487	0.7	9	701.5	18.6
Group 3: Pre-Neoproterozoic inheritance (n = 4; $^{207}Pb/^{206}Pb$ ages tabulated)											
2128512.27.1.1	0.10	202	55	0.28	5.769	2.2	0.07140	0.9	-7	969	18
2128512.21.2.1	0.04	236	81	0.35	7.641	1.2	0.07696	2.8	31	1120	57

Sample. Grain. Spot. Replicate	$^{206}Pb_c$ (%)	U (ppm)	Th (ppm)	^{232}Th /^{238}U	^{238}U/ ^{206}Pb	±1σ (%)	^{207}Pb /^{206}Pb	±1σ (%)	Disc. (%)	Age (Ma)	±1σ (Ma)
2128512.25.1.1	0.02	216	129	0.62	3.611	1.8	0.10250	1.8	6	1670	34
2128512.14.1.1	0.03	133	118	0.92	2.497	1.3	0.13360	2.3	-1	2146	39
Not considered: Instrument instability (n = 3)											
2128512.5.1.1	0.13	188	39	0.22	16.139	5.4	0.05446	1.7	1	387.6	20.2
2128512.26.1.1	-0.02	360	87	0.25	13.543	12.2	0.06546	35.5	43	459.2	54.2
2128512.24.1.1	-0.02	324	61	0.19	10.606	32.9	0.02879	43.2	–	580.8	182.7

3 R7 Prospect; unnamed granite

Table 3.1 Summary of results: unnamed granite at R7 Prospect (GSNSW: PB-11-NYM-16, GA: 2128513).

GA SampleNo	2128513
GSNSW SiteID	PB-11-NYM-16
Parent Unit	—
Stratigraphic Unit	—
Informal Identifier	R7 Prospect granite
Lithology	Granite
Province	Central Lachlan Orogen
1:250 000 Sheet	NYMAGEE (SI/55-2)
1:100 000 Sheet	LACHLAN DOWNS (8033)
Location (GDA94)	32.189140°S, 145.990845°E
Location (MGA94)	Zone 55; 404874 mE, 6438153 mN
Analytical Session No	120014; 13–16 February 2012 (see Appendix Table A1.1 for parameters derived from concurrent measurements of $^{206}Pb/^{238}U$ and $^{207}Pb/^{206}Pb$ reference zircons)
Interpreted Age	422.8 ± 4.9 Ma (n = 4)
Geological Attribution	Magmatic crystallisation age (minimum estimate)
Isotopic Ratio used	$^{206}Pb/^{238}U$ (^{204}Pb-corrected)

3.1 Sampling Details and Geological Relationships

The sample of the unnamed granite at the R7 Prospect (Sandy Creek) comprises a single 3.2 kg segment of diamond drill core intersected in hole DD009 (depth interval 278.8 m to 280.7 m) by Peak Gold Mines Pty. Ltd. The sample is a felsic, fractionated, muscovite-bearing S-type granite.

The granite is inferred by company geologists to be equivalent to the cordierite-biotite bearing S-type Gilgunnia Granite (MacRae, 1989) located immediately south of the R7 Prospect, for which an Early Devonian age has previously inferred due to an intrusive relationship with the Early Devonian Mount Hope Group volcanics and the lower Amphitheatre Group (MacRae, 1989). An unpublished U–Pb SHRIMP age of 422.5 ± 3.6 Ma was determined by Richard Armstrong for the Gilgunnia Granite (PRISE – ANU, pers. comm.); however, the unnamed granite at the R7 Prospect is petrographically similar to the Late Silurian Thule Granite (425.7 ± 2.4 Ma; this volume) ~24 km to the west.

3.2 Petrography

The sample is an equigranular, fine- to medium-grained (predominantly 1–2 mm), tourmaline and muscovite-bearing leucocratic granite (Figure 3.1). It is composed of 35–40% anhedral alkali feldspar, 30–35% anhedral quartz and ~20% lightly sericitised subhedral plagioclase. The alkali feldspar is finely perthitic and characterised by dusty clay alteration and quartz is strained or subgrained with small areas recrystallised to a fine polygonal aggregate. There is minor development of granophyric intergrowth of quartz and alkali feldspar. The granite also contains ~5% stumpy anhedral muscovite crystals (to 1.5 mm), 1% of chlorite-replaced laths of similar size that were probably original biotite, and 2–3% yellow to blue pleochroic irregular and interstitial grains of tourmaline. Trace opaques and rare zircon grains are present.

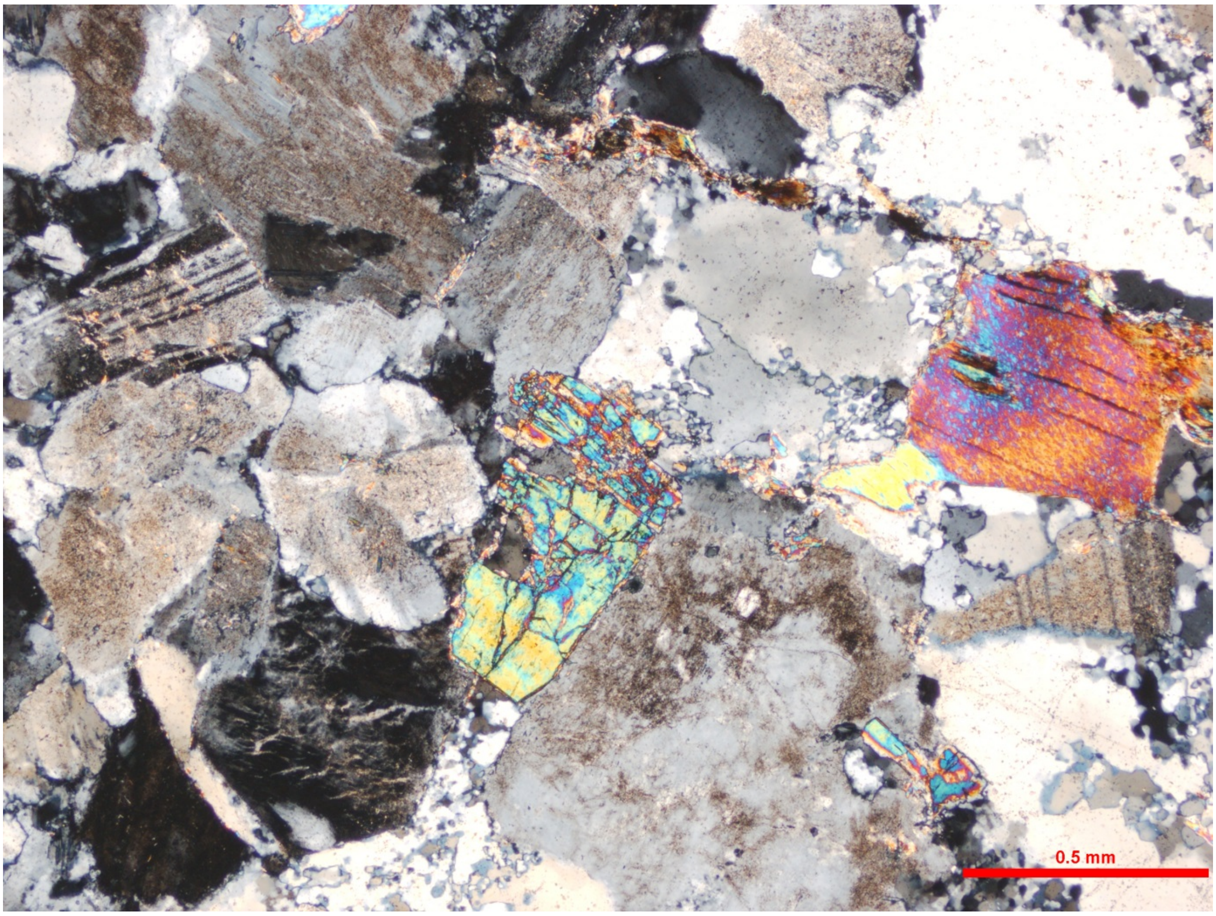


Figure 3.1 Representative photomicrograph of the unnamed granite at R7 Prospect (GSNSW: PB-11-NYM-16, GA: 2128513) taken in cross-polarised light. Equigranular fine- to medium-grained leucocratic granite with abundant perthitic alkali feldspar with dusty alteration (left of scale bar), partly recrystallised strained quartz, lightly sericitised plagioclase and small amounts of late magmatic muscovite (right) and accessory tourmaline (centre). Scale bar is 0.5 mm. Image provided by the Geological Survey of New South Wales.

3.3 Zircon Description

Thirteen zircon grains were extracted from the sample, with abundant pyrite present in the final stages of separation. Zircons range from euhedral grains to anhedral shattered shards. Long axes of grains are 80–130 µm with length to width ratios up to 1:2 in euhedral grains (Figure 3.2).

In transmitted light (TL), zircons grains are pale brown and transparent to slightly translucent. Cracks are present in most grains. Inclusions are present as anhedral blebs, also expressed as external indents in four of the grains (e.g. Figure 3.2, top row, extreme right). Crystal lattice damage is apparent in rim regions in a few of the grains (e.g. Figure 3.2, top row, central grain and grain second from right).

Cathodoluminescence (CL) images reveal core and rim relationships in most grains. Rim regions have very dark CL emission and correlate with crystal lattice damaged regions seen in TL, but it is not clear whether the dark rims are conformable or disconformable on the cores. Cores vary in CL emission from bright to moderate response; moderate response regions exhibit diffuse zoning or banded zoning of variable response (Figure 3.2). Oscillatory zoning with moderate CL emission is present in two grains. Two grains reveal highly luminous core regions, both cores are surrounded by a moderate CL emission diffusely zoned region which is in turn surrounded by the low response rim region (Figure 3.2, bottom row, central grain and third grain from the right).

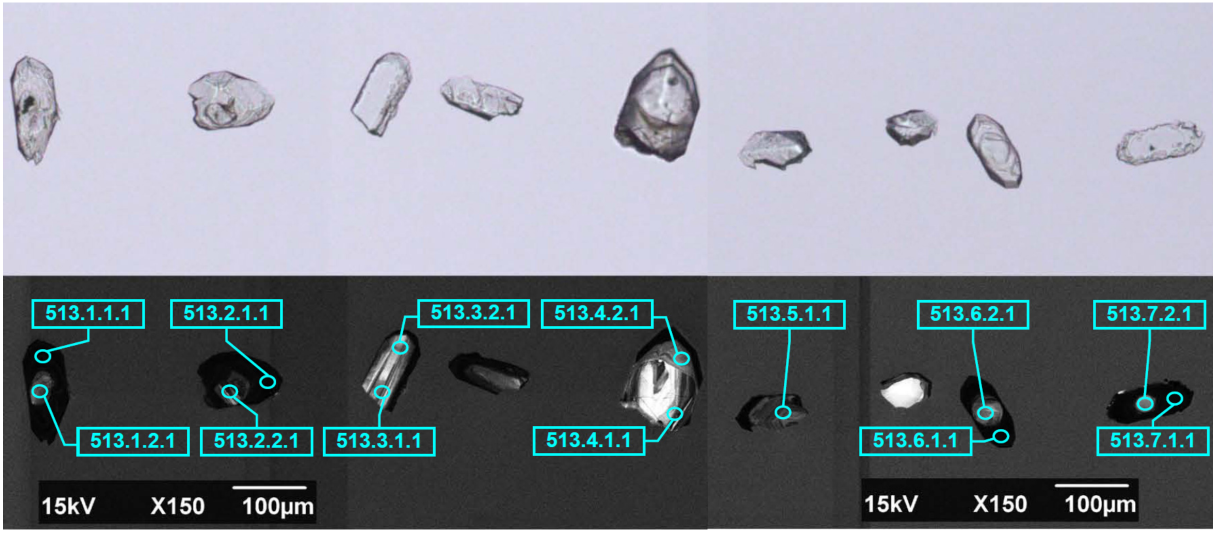


Figure 3.2 Representative zircons of the unnamed granite at R7 Prospect (GSNSW: PB-11-NYM-16, GA: 2128513). Transmitted light images are shown in the upper half and cathodoluminescence images in the lower half. SHRIMP analysis sites are labelled with sample (prefix 2128- not annotated), grain, spot and replicate number. Scale bar is 100 µm.

3.4 U–Pb Isotopic Results

Only seven of the 13 zircons were suitable for analysis. Thirteen analyses were obtained from these seven grains with both core and rim analyses on all but one grain. Results are presented in Figure 3.3, and Figure 3.4 and Table 3.2. There is a wide range of ^{238}U contents (238–10058 ppm, median 398 ppm), with comparatively low $^{232}Th/^{238}U$ (0.02–0.55, median 0.07) and low $^{206}Pb_c$ (maximum 0.27%, median 0.07%).

The 13 analyses can be grouped as follows:

- Group 1: Four analyses (Figure 3.3 and Figure 3.4, yellow fill) from zircons with moderate CL emission and either concentric oscillatory zoning or length-parallel banding. They are characterised by low to moderate ^{238}U (297–718 ppm, median = 354 ppm) and low $^{232}Th/^{238}U$ (0.07–0.36, median 0.23), that yield individual $^{206}Pb/^{238}U$ ages between ~428 Ma and ~417 Ma. These four analyses combine to give a weighted mean $^{206}Pb/^{238}U$ age of 422.8 ± 4.9 Ma (MSWD = 1.10, probability of equivalence = 0.35).
- Group 2: Four analyses (Figure 3.3 and Figure 3.4, grey fill) from dark-CL rims have extremely high ^{238}U contents (6536–10058 ppm), low $^{232}Th/^{238}U$ ratios (0.02–0.03), and low $^{206}Pb_c$ (< 0.01%). Their $^{206}Pb/^{238}U$ ages are ~473 Ma, ~467 Ma, ~460 Ma and ~444 Ma. Despite being located in the outer parts of the grains, their $^{206}Pb/^{238}U$ ages are distinctly older than those in Group 1, and also display significant dispersion (~473 to ~444 Ma). However, their $^{207}Pb/^{206}Pb$ ages are relatively precise and combine to give a weighted mean $^{207}Pb/^{206}Pb$ age of 426.6 ± 4.4 Ma (MSWD = 0.60, probability of equivalence = 0.61), which is indistinguishable from the weighted mean $^{206}Pb/^{238}U$ age of 422.8 ± 4.9 Ma calculated from Group 1.
- Group 3: Two analyses (Figure 3.3 and Figure 3.4, purple fill) with individual $^{206}Pb/^{238}U$ ages that are significantly older than the analyses in Groups 1 and 2 (Table 3.2) and are visible as cores in CL.
- Group 4: Three analyses (Figure 3.3 and Figure 3.4, green fill) with individual $^{207}Pb/^{206}Pb$ ages that are significantly older than the analyses in Groups 1 and 2 (Table 3.2) and are visible as cores in CL.

3.5 Geochronological Interpretation

The $^{206}Pb/^{238}U$ age of 422.8 ± 4.9 Ma obtained from the four analyses in Group 1 is interpreted as an estimate of the emplacement age of the unnamed granite at the R7 Prospect. The $^{207}Pb/^{206}Pb$ age of 426.6 ± 4.4 Ma obtained from the four rim analyses in Group 2 are interpreted to have formed during the same (magmatic crystallisation) event, and the apparent dispersion of their $^{206}Pb/^{238}U$ ages to older values is attributed to crystal/glass matrix effects in these very high-U metamict domains, with reverse discordance arising from preferential sputtering of Pb relative to U from non-crystalline/amorphous parts of the grains (McLaren et al., 1994; Butera et al., 2001). It is not clear why the chemistry of the rim analyses in Group 2 is so different to the analyses in Group 1: one possibility is that the Group 2 rims formed from a highly fractionated magmatic/hydrothermal fluid during the final stages of magmatic crystallisation; supported by the apparent lack of disconformity in the CL images.

Therefore, Groups 1 and 2 represent the magmatic component of the population. Group 2 exhibits U-induced matrix effects that are avoided by the use of the $^{207}Pb/^{206}Pb$ values for age interpretation. The four analyses in Group 1 with a combined $^{206}Pb/^{238}U$ age of 422.8 ± 4.9 Ma, when compared with the $^{206}Pb/^{238}U$ age standard, are well within error and are all of similar age. A comparison of this age with the $^{207}Pb/^{206}Pb$ age of 426.6 ± 4.4 Ma for the four analyses in Group 2 shows it is identical to the $^{206}Pb/^{238}U$ 422.8 ± 4.9 Ma age obtained for the four grains in Group 1, providing confidence that the four analyses in Group 1 represent the age of magmatic crystallisation of the unnamed granite at the R7 Prospect.

The five analyses in Groups 3 and 4 combined are interpreted to represent inheritance of Cambrian to Neoarchean age.

The age of 422.8 ± 4.9 Ma for the unnamed granite at the R7 prospect is indistinguishable from the ages of the Mount Halfway Volcanics (422.8 ± 2.6 Ma) and the Gilgunnia Granite (unpubl: 422.5 ± 3.6 Ma, PRISE – ANU, pers. comm), the sample of which was taken immediately to the south of the R7 Prospect, suggesting the units are equivalent. Petrographic differences between the R7 Prospect intrusion and the Gilgunnia Granite suggests that the R7 Prospect intrusion may be a felsic and fractionated variant.

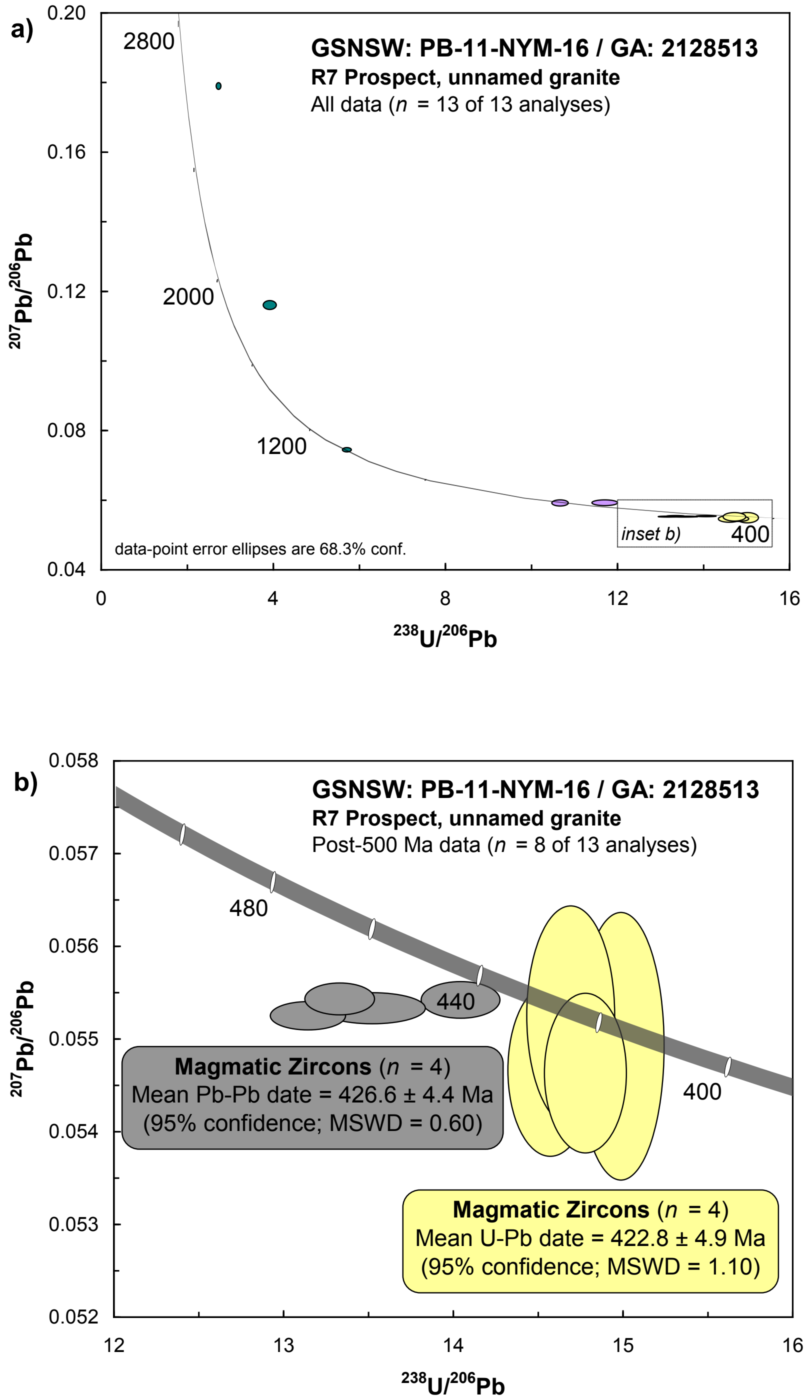
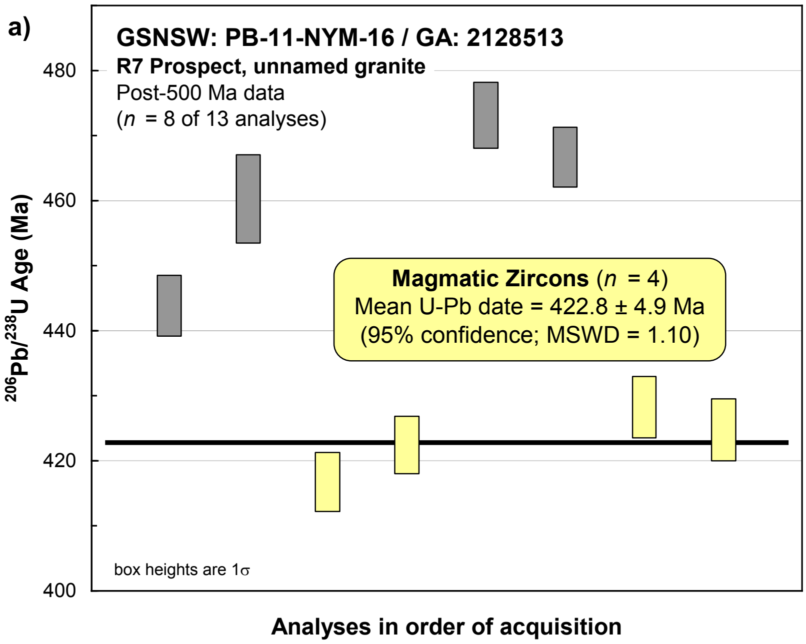


Figure 3.3 SHRIMP U–Pb data for zircons from the unnamed granite at R7 Prospect (GSNSW: PB-11-NYM-16, GA: 2128513). Yellow fill denotes $^{206}Pb/^{238}U$ magmatic population, grey fill denotes $^{207}Pb/^{206}Pb$ magmatic population, purple fill denotes Cambrian–Neoproterozoic inheritance, and green fill denotes pre-Neoproterozoic inheritance. (a) Tera-Wasserberg Concordia diagram showing all data; (b) Tera-Wasserberg Concordia diagram showing post ~480 Ma data shown in box in inset b) of diagram (a).



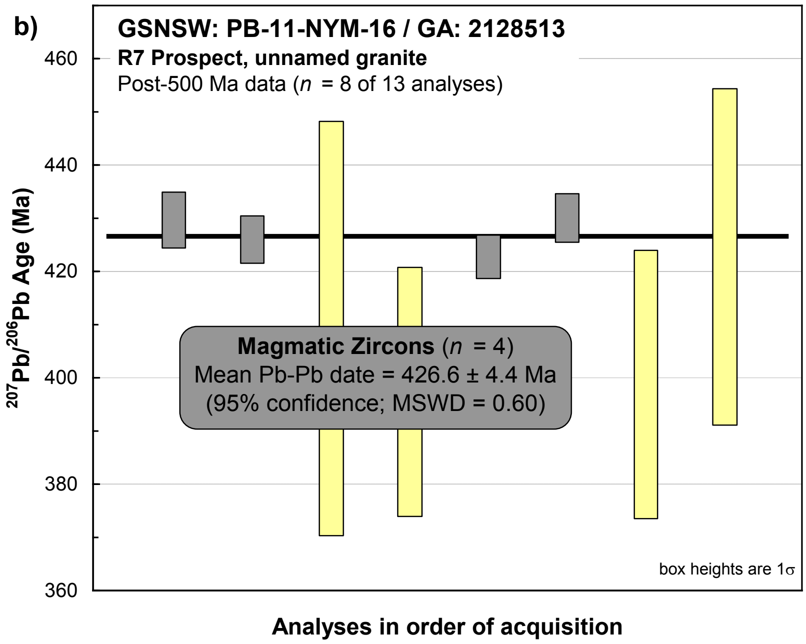


Figure 3.4 Post ~480 Ma SHRIMP U–Pb data for zircons from the unnamed granite at R7 Prospect (GSNSW: PB-11-NYM-16, GA: 2128513). Yellow fill denotes $^{206}Pb/^{238}U$ magmatic population and grey fill denotes $^{207}Pb/^{206}Pb$ magmatic population. Heavy black line represents the weighted mean age of the magmatic population. (a) $^{206}Pb/^{238}U$ ages in order of acquisition; (b) $^{207}Pb/^{206}Pb$ ages in order of acquisition.

Table 3.2 SHRIMP U–Pb isotopic data for zircons from the unnamed granite at R7 Prospect (GSNSW: PB-11-NYM-16, GA: 2128513). Ages are $^{206}Pb/^{238}U$ and $^{207}Pb/^{206}Pb$ as indicated.

Sample. Grain. Spot. Replicate	$^{206}Pb_c$ (%)	U (ppm)	Th (ppm)	$^{232}Th/^{238}U$	$^{238}U/^{206}Pb$	±1σ (%)	$^{207}Pb/^{206}Pb$	±1σ (%)	Disc. (%)	$^{206}Pb/^{238}U$ Age (Ma)	±1σ (Ma)	$^{207}Pb/^{206}Pb$ Age (Ma)	±1σ (Ma)
Group 1: Magmatic zircons (n = 4; $^{206}Pb/^{238}U$ age)													
2128513.3.1.1	0.09	360	126	0.36	14.979	1.1	0.05493	1.7	-2	416.6	4.6	409.2	39.0
2128513.5.1.1	0.27	718	79	0.11	14.770	1.1	0.05463	1.0	-7	422.3	4.4	397.3	23.5
2128513.3.2.1	0.05	348	114	0.34	14.563	1.1	0.05467	1.1	-8	428.1	4.7	398.6	25.2
2128513.4.2.1	0.13	297	21	0.07	14.685	1.2	0.05526	1.4	0	424.7	4.8	422.7	31.7
Group 2: Matrix affected magmatic zircons (n = 4; $^{207}Pb/^{206}Pb$ age)													
2128513.6.1.1	<0.01	10058	219	0.02	13.133	1.1	0.05526	0.2	-12	473.1	5.1	422.7	4.1
2128513.2.1.1	0.01	8542	226	0.03	13.513	1.5	0.05534	0.2	-8	460.2	6.8	425.9	4.5
2128513.1.1.1	<0.01	6356	126	0.02	14.033	1.1	0.05543	0.2	-3	443.7	4.7	429.6	5.3
2128513.7.1.1	<0.01	7623	146	0.02	13.320	1.0	0.05544	0.2	-9	466.7	4.6	430.0	4.6
Group 3: Cambrian–Neoproterozoic inheritance (n = 2; $^{206}Pb/^{238}U$ age)													
2128513.1.2.1	-0.01	379	121	0.33	11.672	1.7	0.05929	0.9	9	529.9	8.6	577.7	18.8
2128513.7.2.1	<0.01	238	5	0.02	10.650	1.2	0.05917	1.0	-1	578.6	6.6	573.2	22.5
Group 3: Pre-Neoproterozoic inheritance (n = 3; $^{207}Pb/^{206}Pb$ age)													
2128513.6.2.1	<0.01	330	119	0.37	5.713	1.2	0.07445	0.6	1	1039.8	11.4	1053.6	12.5
2128513.4.1.1	0.08	398	214	0.55	3.933	2.6	0.11602	0.7	26	1460.6	33.8	1895.7	12.8
2128513.2.2.1	0.26	940	20	0.02	2.736	1.4	0.17890	0.4	28	2008.1	23.6	2642.7	6.1

4 Thule Granite

Table 4.1 Summary of results: Thule Granite (GSNSW: PB-11-NYM-17, GA: 2128514).

GA SampleNo	2128514
GSNSW SiteID	PB-11-NYM-17
Parent Unit	—
Stratigraphic Unit	Thule Granite
Informal Identifier	Previously known as Wirlong Granite (Lloyd, 1936)
Lithology	Granite
Province	Central Lachlan Orogen
1:250 000 Sheet	NYMAGEE (SI/55-2)
1:100 000 Sheet	LACHLAN DOWNS (8033)
Location (GDA94)	32.229810°S, 145.745509°E
Location (MGA94)	Zone 55; 381799 mE, 6433401 mN
Analytical Session No	120014; 13–16 February 2012 (see Appendix Table A1.1 for parameters derived from concurrent measurements of $^{206}Pb/^{238}U$ and $^{207}Pb/^{206}Pb$ reference zircons)
Interpreted Age	425.7 ± 2.4 Ma (n = 28)
Geological Attribution	Magmatic crystallisation
Isotopic Ratio used	$^{206}Pb/^{238}U$ (^{204}Pb-corrected)

4.1 Sampling Details and Geological Relationships

The sample comprises 27 kg of clean fresh rock chips obtained from RC drill hole CCRC 535 at depth interval 28–30 m, collared in granite saprolite in the ‘Wontawinta Dome’ near the Wontawinta silver mine by Cobar Consolidated Resources. The sample consists of felsic, fractionated, peraluminous quartz, two-feldspar, muscovite granite.

The Thule Granite (Lloyd, 1938; Brunker, 1973) is a fault-bounded batholith forming a narrow meridonial strip up to 8.5 km wide and over 70 km in length (McRae, 1989) extending beyond the boundaries of LACHLAN DOWNS, onto MOUNT ALLEN (NYMAGEE) and WRIGHTVILLE (COBAR). The granite is exposed due to movement along a steeply dipping fault resulting in contact with the Amphitheatre, Winduck and Mulga Downs groups (MacRae, 1989; Bull et al., 2008). The granite is inferred to underlie the volcanics of the Mount Hope Group (Scheibner, 1987; Bull et al., 2008); although the contact between the two is not apparent, basal strata of the Mount Kennan Volcanics—the lowest unit of the Mount Hope Group—contains clasts of metasedimentary rock purportedly derived from the Thule Block (Scheibner, 1987). The Mount Hope Group also includes the Mount Halfway Volcanics (422.8 ± 2.6 Ma, this volume) and the Mount Hope Volcanics (411 ± 4 Ma, Bull et al., 2008).

A previous biotite K-Ar age of 422 ± 6 Ma, and muscovite K–Ar ages of 408 ± 6 Ma and 416 ± 6 Ma were obtained by Pogson and Hilyard (1981), who noted that the oldest isotopic age of 422 ± 6 Ma was likely closest to the true age of emplacement, and suggested the Thule Granite is probably Mid-Silurian in age. The Thule Granite is texturally and compositionally similar to the Erimeran Granite (427.2 ± 2.4 Ma; Black, 2007).

The granite at the Wontawinta mine site (nov. “Wirlong Granite” in Lloyd, 1936) has been previously assumed to be part of the extensive Thule Granite located to the southeast. Dating of this unit will determine if the granite is the same age as other dated components.

4.2 Petrography

The Thule Granite is an S-type peraluminous, porphyritic, two-feldspar, quartz, biotite-muscovite granite (Pogson and Hilyard, 1981; Scheibner, 1987). MacRae (1989) noted tabular feldspars between 2 and 4 cm in length with rare megacrysts up to 8 cm, quartz phenocrysts generally 1–2 cm in diameter and biotite up to 1 cm in length, in a groundmass of predominantly quartz, feldspar, muscovite and biotite grains between 3 and 8 mm in length. MacRae (1989) further noted accessory minerals discernable in thin section include tourmaline, apatite, Ti-magnetite, and zircon with alteration minerals of chlorite, rutile, sericite, titanite, epidote and fluorite.

4.3 Zircon Description

The zircons are predominantly euhedral to subhedral elongate to stubby grains with well-formed to subrounded facets and fractured grains. Long axes are 80–400 μm. Grain length to width is variable between 1:1 and 5:1 (Figure 4.1).

In transmitted light, zircons are predominantly transparent to translucent and colourless. Subhedral grains are colourless, transparent to translucent, and represent approximately 5% of the population. Many grains are free of cracks and inclusions, with axial and xenocrystic-core related cracks present in approximately 30% of grains, and axial and core related inclusions present in approximately 20% of grains (Figure 4.1).

Cathodoluminescence (CL) imaging reveals a range of internal structures and textures with high to low CL emission response. Cores are common and are truncated by concentrically zoned rims. Cores range from moderate CL emission and diffusely zoned to very low response and small (~30 μm) with wide concentrically zoned rims, to very bright and large (up to 120 μm) with small rims (< 10 μm). Other cores variably exhibit convolute or concentric zoning with moderate CL emission and finely zoned, moderate CL emission, wide rims. Coreless grains have fine concentric zoning or display fine to broad length-parallel banding with moderate to high CL emission (Figure 4.1).

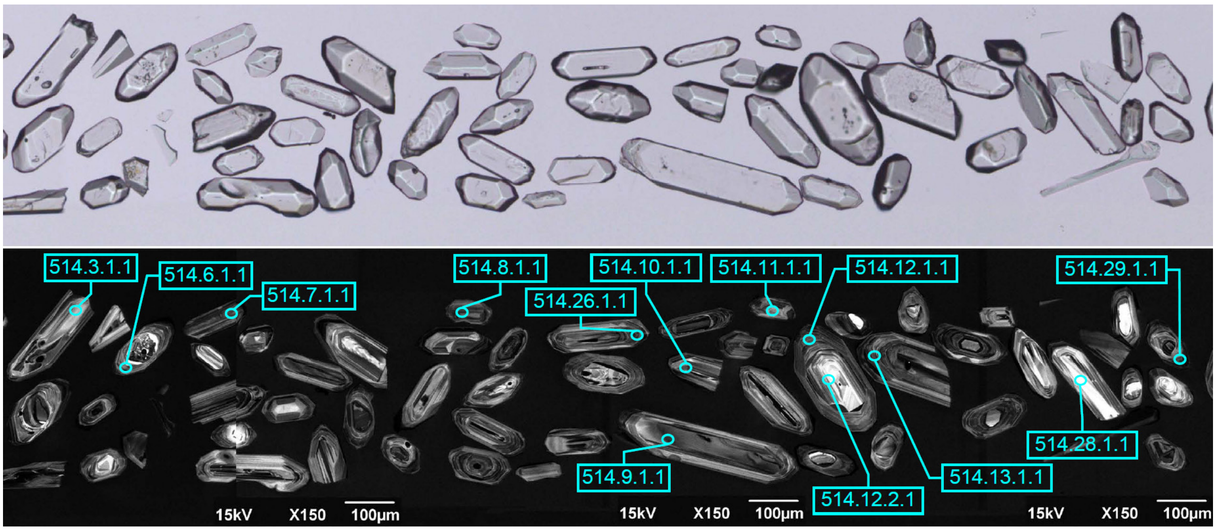


Figure 4.1 Representative zircons of the Thule Granite (GSNSW: PB-11-NYM-17, GA: 2128514). Transmitted light image is shown in the upper half and cathodoluminescence image in the lower half. SHRIMP analysis sites are labelled with sample (prefix 2128- not annotated), grain, spot and replicate number. Scale bar is 100 μm.

4.4 U–Pb Isotopic Results

Thirty-one analyses were obtained from 29 zircons. Results are presented in Figure 4.2 and Table 4.2. The analysed zircons are characterised by a low to moderate range of ^{238}U contents (88–538 ppm, median 284 ppm), with low to moderate $^{232}Th/^{238}U$ (0.04–0.82, median 0.22) and low $^{206}Pb_c$ (maximum 0.62%, median 0.03%).

The 31 analyses can be grouped using textural and isotopic criteria as follows:

- Group 1: 28 analyses (Figure 4.2, yellow fill; Table 4.2) from concentrically zoned rims and interiors of coreless grains with individual $^{206}Pb/^{238}U$ ages between ~435 Ma and ~417 Ma. The analyses combine to produce a weighted mean $^{206}Pb/^{238}U$ age of 425.7 ± 2.4 Ma (95% confidence, MSWD = 0.94, probability of equivalence = 0.55).
- Group 2: two analyses (Figure 4.2, purple fill; Table 4.2) from core regions with individual $^{206}Pb/^{238}U$ ages of ~582 Ma and ~498 Ma.
- Group 3: one analysis of a core with an individual $^{207}Pb/^{206}Pb$ age of ~1076 Ma (Figure 4.2, green fill; Table 4.2).

4.5 Geochronological Interpretation

The weighted mean $^{206}Pb/^{238}U$ age of 425.7 ± 2.4 Ma for the 28 analyses in Group 1 is interpreted to be the magmatic crystallisation age of the Thule Granite.

The three analyses in Groups 2 and 3 combined are interpreted as inheritance of Cambrian to Mesoproterozoic age.

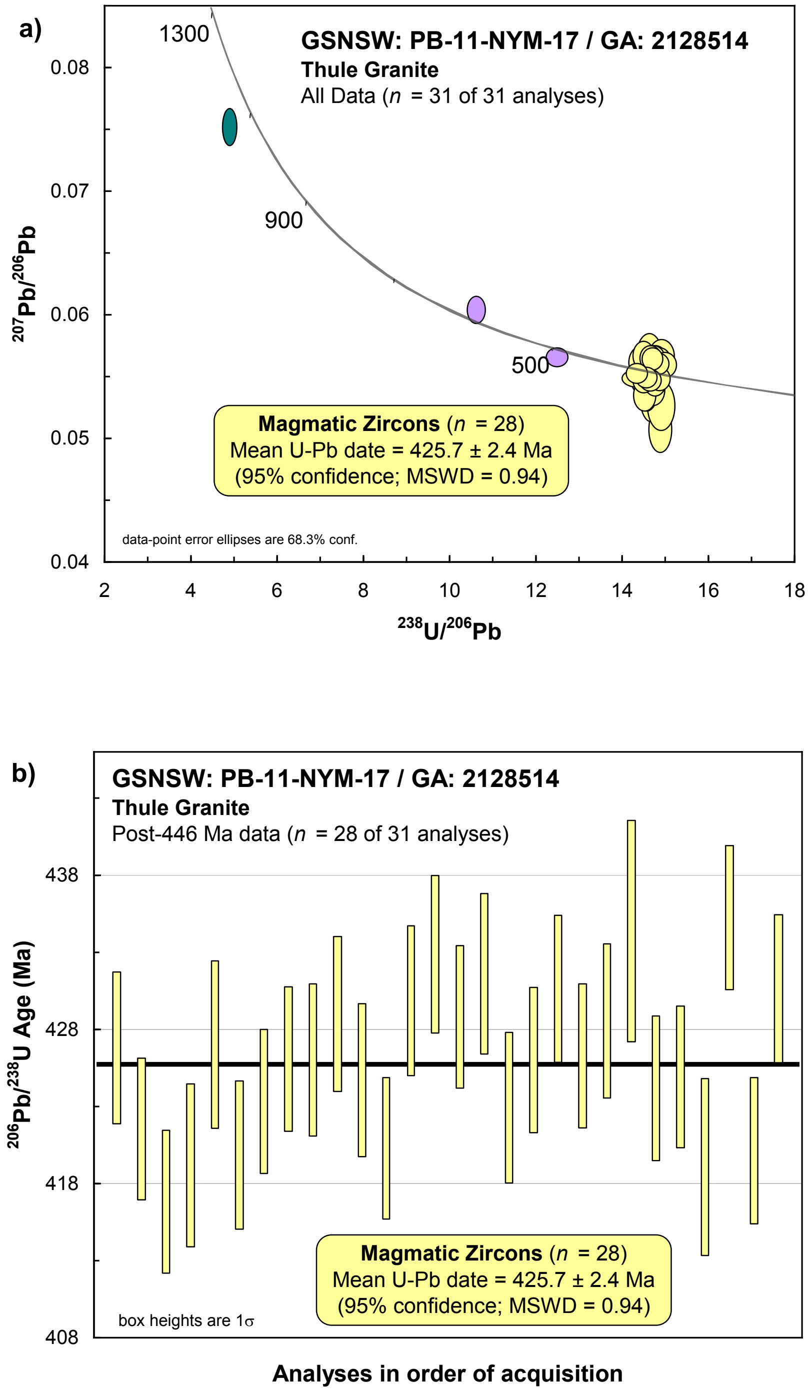


Figure 4.2 SHRIMP U–Pb data for zircons from the Thule Granite (GSNSW: PB-11-NYM-17, GA: 2128514). Yellow fill denotes magmatic population, purple fill denotes Cambrian–Neoproterozoic inheritance, and green fill denotes Mesoproterozoic inheritance. (a) Tera-Wasserberg Concordia diagram; (b) Post ~446 Ma $^{206}Pb/^{238}U$ ages in order of acquisition; heavy black line represents the weighted mean $^{206}Pb/^{238}U$ age of the magmatic population.

Table 4.2 SHRIMP U–Pb isotopic data for zircons from the Thule Granite (GSNSW: PB-11-NYM-17, GA: 2128514). Ages are $^{206}Pb/^{238}U$ unless otherwise indicated.

Sample. Grain. Spot. Replicate	$^{206}Pb_c$ (%)	U (ppm)	Th (ppm)	$^{232}Th/^{238}U$	$^{238}U/^{206}Pb$	±1σ (%)	$^{207}Pb/^{206}Pb$	±1σ (%)	Disc. (%)	Age (Ma)	±1σ (Ma)
Group 1: Magmatic zircons (n = 28)											
2128514.1.1.1	0.06	302	99	0.34	14.973	1.1	0.05596	1.2	8	416.8	4.6
2128514.28.1.1	0.13	94	47	0.52	14.890	1.4	0.05264	2.5	-35	419.0	5.7
2128514.2.1.1	0.04	164	46	0.29	14.886	1.3	0.05667	1.6	13	419.1	5.3
2128514.6.1.1	0.63	241	38	0.16	14.862	1.2	0.05071	2.4	-87	419.8	4.8
2128514.30.1.1	-0.04	284	31	0.11	14.851	1.2	0.05627	1.3	10	420.1	4.8
2128514.13.1.1	0.04	325	69	0.22	14.845	1.1	0.05481	1.1	-4	420.2	4.6
2128514.5.1.1	-0.03	348	63	0.19	14.800	1.1	0.05605	1.1	7	421.5	4.6
2128514.17.1.1	0.03	212	46	0.22	14.749	1.2	0.05637	1.3	10	422.9	4.9
2128514.7.1.1	0.14	309	28	0.10	14.735	1.1	0.05454	1.3	-8	423.3	4.7
2128514.26.1.1	-0.08	328	55	0.17	14.705	1.1	0.05647	1.2	10	424.1	4.7
2128514.11.1.1	0.06	197	47	0.25	14.685	1.2	0.05390	1.5	-16	424.7	5.0
2128514.27.1.1	-0.05	412	75	0.19	14.678	1.1	0.05643	1.0	10	424.9	4.6
2128514.18.1.1	-0.10	303	63	0.22	14.639	1.1	0.05556	1.2	2	426.0	4.7
2128514.9.1.1	0.16	208	31	0.15	14.639	1.2	0.05371	2.9	-19	426.0	5.0
2128514.8.1.1	-0.08	318	38	0.12	14.636	1.1	0.05650	1.2	10	426.0	4.7
2128514.21.1.1	<0.01	330	39	0.12	14.629	1.1	0.05471	1.0	-7	426.3	4.7
2128514.4.1.1	0.08	228	73	0.33	14.611	1.2	0.05501	1.4	-4	426.7	4.9
2128514.3.1.1	-0.19	132	95	0.74	14.603	1.3	0.05665	2.1	11	427.0	5.4
2128514.22.1.1	0.03	209	50	0.25	14.550	1.2	0.05411	2.4	-15	428.5	5.0
2128514.15.1.1	0.03	401	70	0.18	14.540	1.1	0.05492	1.0	-5	428.8	4.6
2128514.10.1.1	-0.03	185	106	0.59	14.533	1.2	0.05536	1.4	-1	429.0	5.1
2128514.12.1.1	0.19	251	37	0.15	14.503	1.2	0.05348	1.6	-24	429.8	4.9
2128514.19.1.1	0.06	315	99	0.33	14.477	1.15	0.05469	1.21	-8	430.6	4.8
2128514.23.2.1	-0.16	320	72	0.23	14.476	1.2	0.05670	1.3	11	430.6	4.8
2128514.16.1.1	0.07	161	39	0.25	14.443	1.2	0.05496	1.7	-5	431.6	5.2
2128514.14.1.1	-0.06	187	41	0.23	14.399	1.2	0.05613	1.5	6	432.8	5.1
2128514.25.1.1	0.02	538	83	0.16	14.347	1.7	0.05485	0.9	-7	434.4	7.2
2128514.29.1.1	0.03	434	35	0.08	14.317	1.1	0.05525	1.0	-3	435.2	4.7
Group 2: Cambrian–Neoproterozoic inheritance (n = 2)											
2128514.24.1.1	0.03	383	226	0.61	12.463	1.3	0.05656	0.9	-5	497.5	6.2
2128514.23.1.1	0.05	184	6	0.04	10.588	1.3	0.06042	1.2	6	581.8	7.1
Group 3: Mesoproterozoic inheritance (n = 1; $^{207}Pb/^{206}Pb$ age tabulated)											
2128514.12.2.1	0.18	88	69	0.82	4.857	2.3	0.07527	1.3	-13	1076	27

5 De Nardi Prospect; unnamed granite

Table 5.1 Summary of results: unnamed granite at De Nardi Prospect (GSNSW: PB-11-NYM-18, GA: 2128515).

GA SampleNo	2128515
GSNSW SiteID	GSNSW PB-11-NYM-18
Parent Unit	—
Stratigraphic Unit	—
Informal Identifier	De Nardi granite
Lithology	Granite
Province	Central Lachlan Orogen
1:250 000 Sheet	NYMAGEE (SI/55-2)
1:100 000 Sheet	LACHLAN DOWNS (8033)
Location (GDA94)	32.014803°S, 145.805472°E
Location (MGA94)	Zone 55; 387185 mE, 6457300 mN
Analytical Session No	120014; 13–16 February 2012 (see Appendix Table A1.1 for parameters derived from concurrent measurements of $^{206}Pb/^{238}U$ and $^{207}Pb/^{206}Pb$ reference zircons)
Interpreted Age	427.2 ± 3.1 Ma (n = 13)
Geological Attribution	Magmatic crystallisation
Isotopic Ratio used	$^{206}Pb/^{238}U$ (^{204}Pb-corrected)

5.1 Sampling Details and Geological Relationships

The sample of the unnamed granite at De Nardi Prospect comprises a 3.9 kg single segment of clean diamond drill core from hole CCR-144 at depth interval 366.68 m–370.00 m obtained by Cobar Consolidated Resources.

The granite was intersected beneath the De Nardi Prospect during drilling and is previously undescribed and undated.

5.2 Petrography

The sample is a partially carbonate- and sericite-altered, coarse-grained, leucocratic granite (Figure 5.1). Many of the grains are 6–7 mm in size with a few alkali feldspar grains to 10 mm in length. The granite contains abundant anhedral alkali feldspar grains (30–35 modal %), which are simply twinned and have well-developed perthite texture, enhanced by the dusty alteration of the alkali feldspar. Quartz (35–40 modal %) occurs as single anhedral grains but more commonly in patches of several grains with well-developed intergrown (consertal) boundaries. For the most part, plagioclase occurs as tabular grains that are almost entirely replaced by sericite and less abundant carbonate, apart from the narrow outer rim of clear albite, which in some instances is polysynthetic twinned. There are a few much smaller plagioclase grains that are mainly unaltered. The estimated modal content for plagioclase is probably 15–20%; this includes a few tabular grains that have been replaced by coarser grained white mica. The remainder of the mode includes a few percent of ex-biotite laths to (1.5 mm), which have been replaced by chlorite and white mica and a few interstitial muscovite grains of similar size. Accessory minerals include opaques, apatite, pleochroic blue tourmaline and rare small zircon.

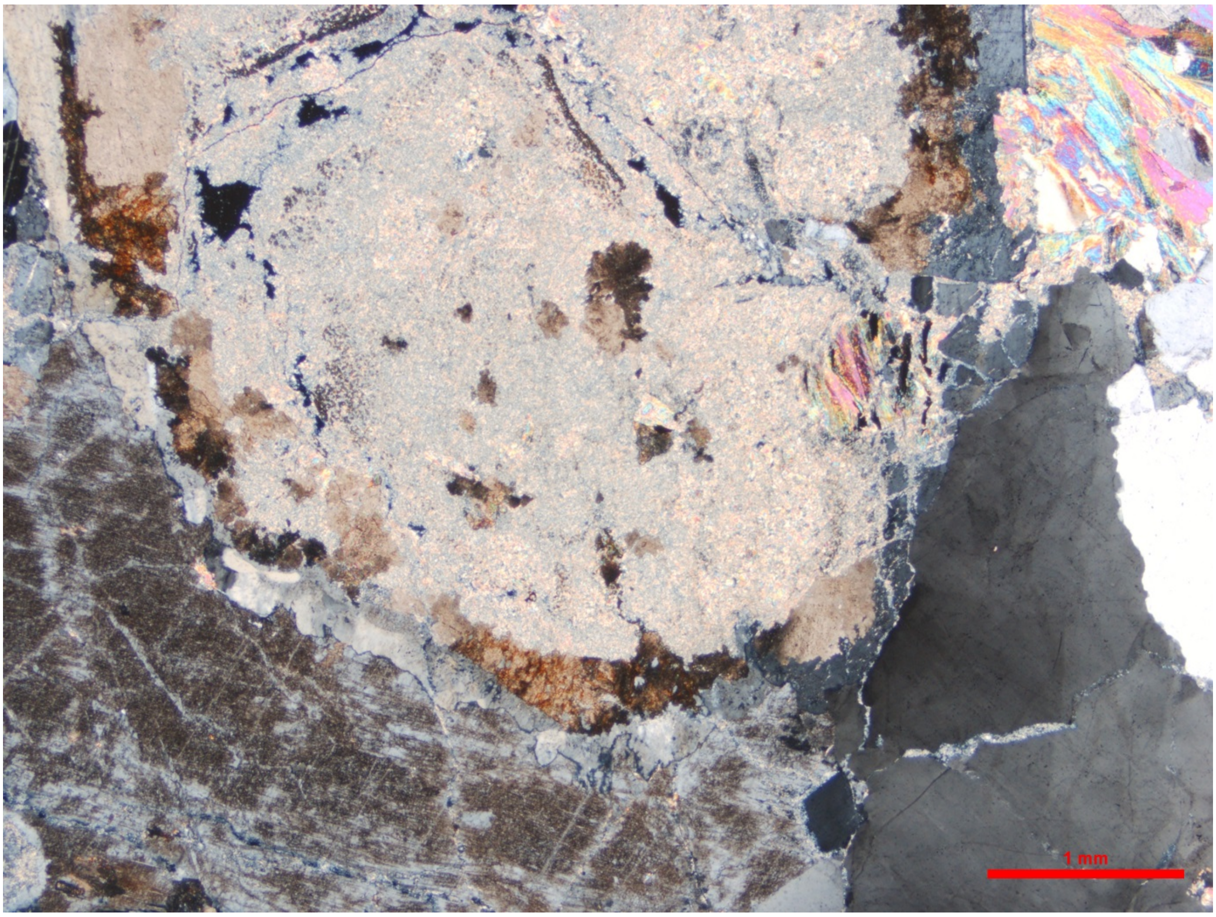


Figure 5.1 Representative photomicrograph of the unnamed granite at De Nardi Prospect (GSNSW: PB-11-NYM-18, GA: 2128515) taken in cross-polarised light. Coarse-grained, leucocratic granite featuring a large mainly sericite-altered plagioclase grain with a narrow outer band of carbonate replacement and a narrow rim of clear albite (best observed adjacent to the alkali feldspar in lower left of photo). The alkali feldspar is perthitic and clay-altered. The image also shows part of a consertal-textured patch of quartz (lower right) and probable late-magmatic muscovite. Scale bar is 1 mm. Image provided by the Geological Survey of New South Wales.

5.3 Zircon Description

Zircons from this sample vary from euhedral with well-formed facets and sub-prismatic terminations to sub-angular shards. Long axes of intact grains are 40–280 µm and length to width varies from 1.5:1 to 9:1, with the majority of grains being strongly elongate (5:1 and higher; Figure 5.2).

In transmitted light, zircons are predominantly transparent to slightly translucent and are colourless to pale brown (Figure 5.2). Very few cracks and inclusions are present (< 5% of the population).

Cathodoluminescence (CL) imaging reveals consistent internal structures across the acicular population with a broadly diffuse moderate CL emission central region surrounded by a fine oscillatory zoned moderate emission rim region. Stubbier grains exhibit high-contrast concentric zoning around low CL emission diffuse cores (Figure 5.2).

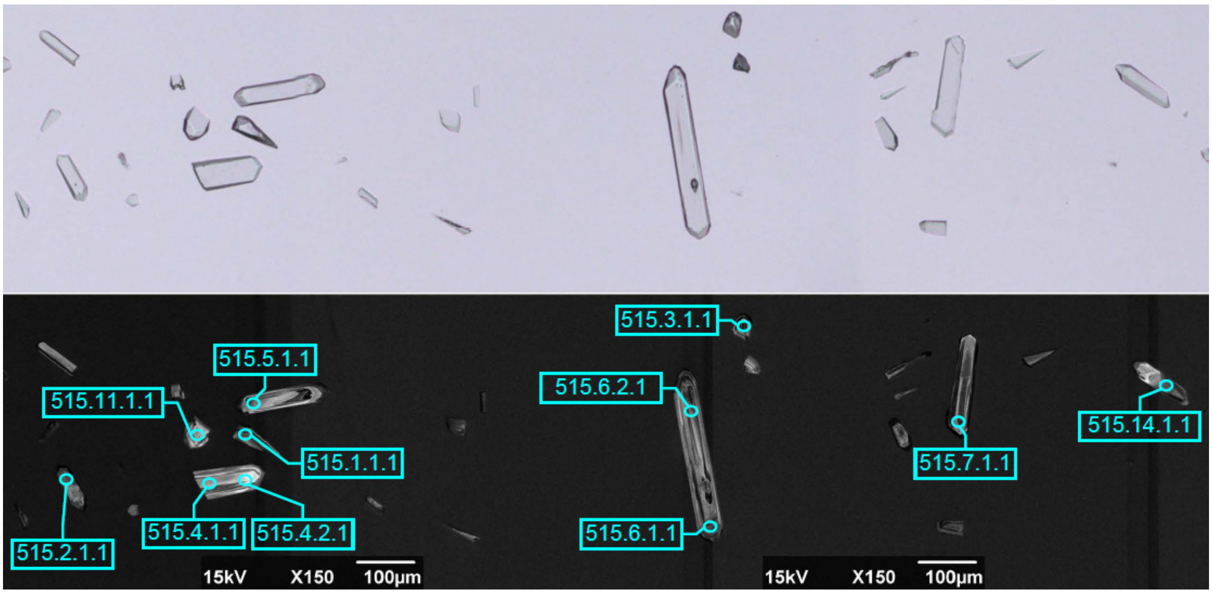


Figure 5.2 Representative zircons of the unnamed granite at De Nardi Prospect (GSNSW: PB-11-NYM-18, GA: 2128515). Transmitted light image is shown in the upper half and cathodoluminescence image in the lower half. SHRIMP analysis sites are labelled with sample (prefix 2128- not annotated), grain, spot and replicate number. Scale bar is 100 µm.

5.4 U–Pb Isotopic Results

Few grains were suitable for analysis as most of the smaller elongate grains were plucked from the mount surface during the polishing process, and only larger grains remained (Figure 5.2).

Seventeen analyses were obtained from 14 zircons; results are presented in Figure 5.3 and Table 5.2. The analysed zircons are characterised by a low to moderate range of ^{238}U contents (172–607 ppm, median 358 ppm), with low $^{232}Th/^{238}U$ (0.06–0.43, median 0.19).

Two analyses were attempted on grain 10 (Figure 5.3, white fill); both yielded anomalously large uncertainties and appear to be adversely affected by down-hole heterogeneity during analysis. These two analyses are not considered further.

The remaining 15 analyses are characterised by low $^{206}Pb_c$ (maximum 0.24%, median 0.06%) and can be divided into three groups based on textural and isotopic criteria:

- Group 1: 13 analyses (Figure 5.3, yellow fill) of euhedral, predominantly elongate zircons with individual $^{206}Pb/^{238}U$ ages between ~433 Ma and ~414 Ma. The analyses combine to produce a weighted mean $^{206}Pb/^{238}U$ age of 427.2 ± 3.1 Ma (95% confidence, MSWD = 1.25, probability of equivalence = 0.24).
- Group 2: one analysis from a discrete sub-angular shard (Figure 5.2) with an individual $^{206}Pb/^{238}U$ age of ~499 Ma (Figure 5.3, purple fill).
- Group 3: one analysis from the core of a stubby euhedral grain with an individual $^{207}Pb/^{206}Pb$ age of ~2263 Ma (Figure 5.3, green fill).

5.5 Geochronological Interpretation

The weighted mean $^{206}Pb/^{238}U$ age of 427.2 ± 3.1 Ma for the 13 analyses in Group 1 is interpreted as the magmatic crystallisation age of the unnamed granite intersected at the De Nardi Prospect.

The two analyses in Groups 2 and 3 combined are interpreted as inheritance of Cambrian to Paleoproterozoic age.

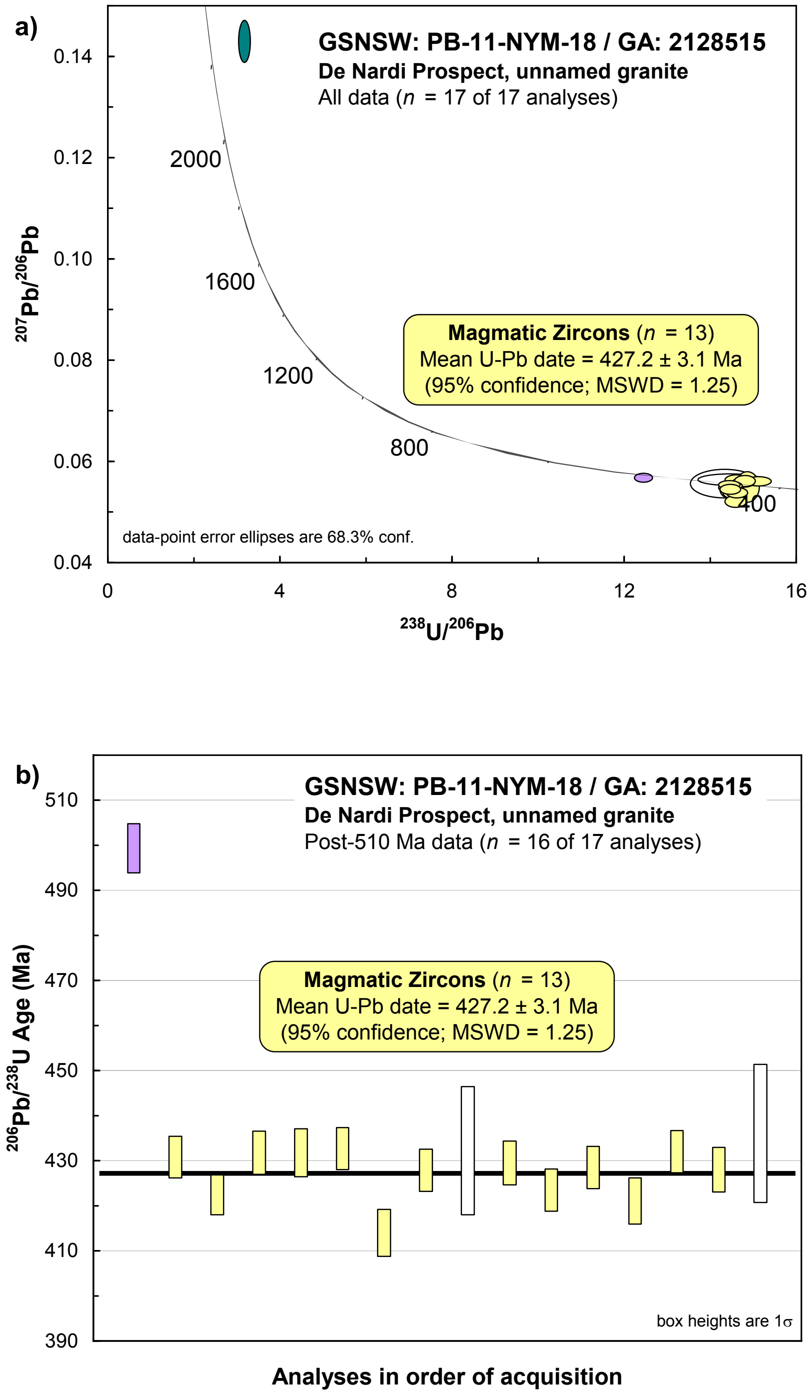


Figure 5.3 SHRIMP U–Pb data for zircons from the unnamed granite at the De Nardi Prospect (GSNSW: PB-11-NYM-18, GA: 2128515). Yellow fill denotes magmatic population, purple fill denotes Cambrian inheritance, green fill denotes Paleoproterozoic inheritance, and white fill denotes analyses not considered. (a) Tera-Wasserberg Concordia diagram; (b) Post ~510 Ma $^{206}Pb/^{238}U$ ages in order of acquisition; heavy black line represents the weighted mean $^{206}Pb/^{238}U$ age of the magmatic population.

Table 5.2 SHRIMP U–Pb isotopic data for zircons from the unnamed granite at De Nardi Prospect (GSNSW: PB-11-NYM-18, GA: 2128515). Ages are $^{206}Pb/^{238}U$ unless otherwise indicated.

Sample. Grain. Spot. Replicate	$^{206}Pb_c$ (%)	U (ppm)	Th (ppm)	$^{232}Th/^{238}U$	$^{238}U/^{206}Pb$	±1σ (%)	$^{207}Pb/^{206}Pb$	±1σ (%)	Disc. (%)	Age (Ma)	±1σ (Ma)
Group 1: Magmatic zircons (n = 13)											
2128515.7.1.1	0.02	384	77	0.21	15.087	1.3	0.05607	1.1	9	413.7	5.2
2128515.4.2.1	0.11	172	37	0.22	14.824	1.3	0.05494	3.6	-3	420.8	5.1
2128515.3.1.1	0.01	607	253	0.43	14.774	1.1	0.05612	1.3	8	422.2	4.4
2128515.6.2.1	-0.08	358	71	0.21	14.736	1.2	0.05587	1.1	6	423.3	4.7
2128515.8.1.1	0.14	380	31	0.09	14.579	1.1	0.05381	1.2	-18	427.7	4.6
2128515.15.1.1	<0.01	244	41	0.18	14.575	1.2	0.05627	1.2	8	427.8	4.9
2128515.13.1.1	0.24	331	110	0.34	14.555	1.1	0.05212	1.5	-49	428.4	4.7
2128515.11.1.1	0.17	265	85	0.33	14.522	1.2	0.05385	1.6	-18	429.3	4.9
2128515.2.1.1	-0.01	388	33	0.09	14.462	1.1	0.05519	0.9	-3	431.0	4.6
2128515.4.1.1	0.06	297	69	0.24	14.442	1.2	0.05442	2.1	-11	431.6	4.8
2128515.5.1.1	0.16	406	71	0.18	14.441	1.3	0.05478	1.2	-7	431.6	5.4
2128515.14.1.1	0.13	391	22	0.06	14.432	1.1	0.05445	1.2	-11	431.9	4.7
2128515.6.1.1	-0.07	436	77	0.18	14.410	1.1	0.05536	1.0	-1	432.5	4.6
Group 2: Cambrian inheritance (n = 1)											
2128515.1.1.1	0.08	344	108	0.32	12.417	1.1	0.05676	1.0	-4	499.3	5.4
Group 3: Paleoproterozoic inheritance (n = 1; $^{207}Pb/^{206}Pb$ age tabulated)											
2128515.9.1.1	0.01	431	78	0.19	3.191	2.8	0.14291	1.9	25	2263	33
Not considered: affected by down-hole heterogeneity (n = 2)											
2128515.10.1.1	-0.11	293	34	0.12	14.425	3.4	0.05636	1.3	8	432.1	14.3
2128515.10.2.1	-0.07	337	36	0.11	14.295	3.7	0.05561	3.3	0	435.9	15.4

6 'Cuttaburra granite'

Table 6.1 Summary of results: 'Cuttaburra granite' (GSNSW: PB-11-THOM-01, GA: 2128516).

GA SampleNo	2128516
GSNSW SiteID	PB-11-THOM-01
Parent Unit	—
Stratigraphic Unit	—
Informal Identifier	'Cuttaburra granite'
Lithology	Granite
Province	Thomson Orogen
1:250 000 Sheet	LOUTH (SH/55-9)
1:100 000 Sheet	THOOLABOOL (7736)
Location (GDA94)	30.644798°S, 144.213198°E
Location (MGA94)	Zone 55; 232923 mE, 6606450 mN
Analytical Session No	120014; 13–16 February 2012 (see Appendix Table A1.1 for parameters derived from concurrent measurements of $^{206}Pb/^{238}U$ and $^{207}Pb/^{206}Pb$ reference zircons)
Interpreted Age	428.3 ± 2.8 Ma (n = 19)
Geological Attribution	Magmatic crystallisation
Isotopic Ratio used	$^{206}Pb/^{238}U$ (^{204}Pb-corrected)

6.1 Sampling Details and Geological Relationships

The sample of the 'Cuttaburra granite' comprises a single 920 g segment of diamond drill core. The granite was intersected in the CUT A (drillhole 01) at 597 m depth by Thomson Resources in the Cuttaburra region of the Thomson Orogen (Rothery, 2013). The sample is a felsic granite, with pyrrhotite veining and minor phyllic alteration.

Granites in the region range from Silurian S-types through Devonian I-types to the Triassic tin-mineralised granites at Doradilla, southeast of Bourke.

The 'Cuttaburra granite' is previously undescribed and undated. A magmatic crystallisation age will provide additional age data to (1) constrain geological events in the local area; (2) provide additional age data for comparison with other granites in the region; and (3) inform geological modelling for exploration.

6.2 Petrography

The sample consists of a medium-grained porphyritic granodiorite (Figure 6.1) in which crystals ranging up to 4.5 mm in size of feldspar, quartz and altered biotite occur in a coarsely recrystallised groundmass (~20% of the rock). Of the larger crystal fraction, plagioclase (~40% of the rock), occurs as mostly well-formed subhedral and a few euhedral tabular grains, some of which are very finely concentrically zoned. Andesine compositions (An46) were obtained on several cleavage sections. Some of the plagioclase component has mildly to strongly sericite- and fine epidote- and rare carbonate-altered cores. Quartz (~20%) occurs as hexagonal to strongly resorbed crystals (to 4 mm) that are slightly recrystallised around the margins. Alkali feldspar (~10%) occurs as smaller (to 1 mm), very clear anhedral grains, some of which are weakly and very finely micropoikilitic. Biotite laths (7–10%), are almost entirely chlorite-replaced anhedral scruffy laths (to 3 mm), however, the relicts are foxy red/brown in colour. The coarsely microcrystalline groundmass consists of polygonal quartz, alkali feldspar and minor plagioclase. There is a small amount (~2%) of muscovite in the rock, most of which is intergrown with quartz and alkali feldspar in the groundmass and is, therefore, considered to be late magmatic; however, some occurs with chlorite as a replacement of biotite laths. Accessory minerals include irregular opaques, apatite and zircon.

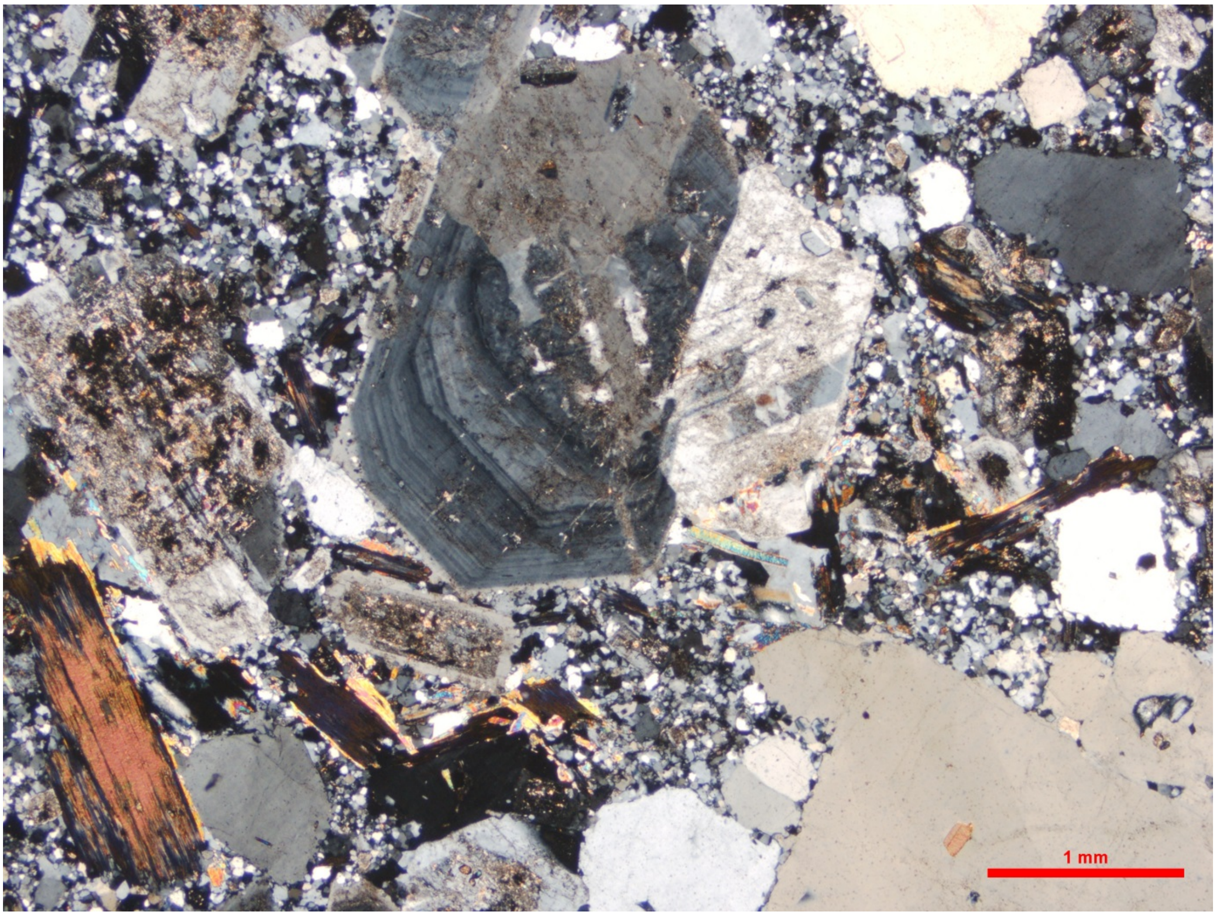


Figure 6.1 Representative photomicrograph of the 'Cuttaburra granite' (GSNSW: PB-11-THOM-01, GA: 2128516) taken in cross-polarised light. Granodiorite showing porphyritic texture. Well-formed, zoned plagioclase crystals, embayed quartz, minor alkali feldspar (small grain below central plagioclase) and mostly altered red/brown biotite crystals occur in a recrystallised groundmass composed mainly of quartz and alkali feldspar. Scale bar is 1 mm. Image provided by the Geological Survey of New South Wales.

6.3 Zircon Description

Zircons from this sample of the ‘Cuttaburra granite’ vary from euhedral with prismatic terminations to subhedral with formed facets and stubby to rounded terminations. Long axes of euhedral grains are 30–150 µm and length to width varies from 1:1 to 4:1 (Figure 6.2).

In transmitted light, the zircons are predominantly transparent and colourless to pale brown. Many grains exhibit pervasive cracking. Inclusions are rare (Figure 6.2).

Cathodoluminescence (CL) imaging reveals a range of internal zoning patterns within a generally high-contrast CL emission population. Fine-band, high contrast oscillatory zoning surrounds either high CL emission or low emission cores, all with diffuse or broad banding. Approximately 30% of the population exhibits a feature of a broad dark band surrounding a moderate intensity core, with a high response fine band forming an outer rim. Coreless grains with length-parallel banding show broad diffuse textures and moderate to high contrast CL emission (Figure 6.2).

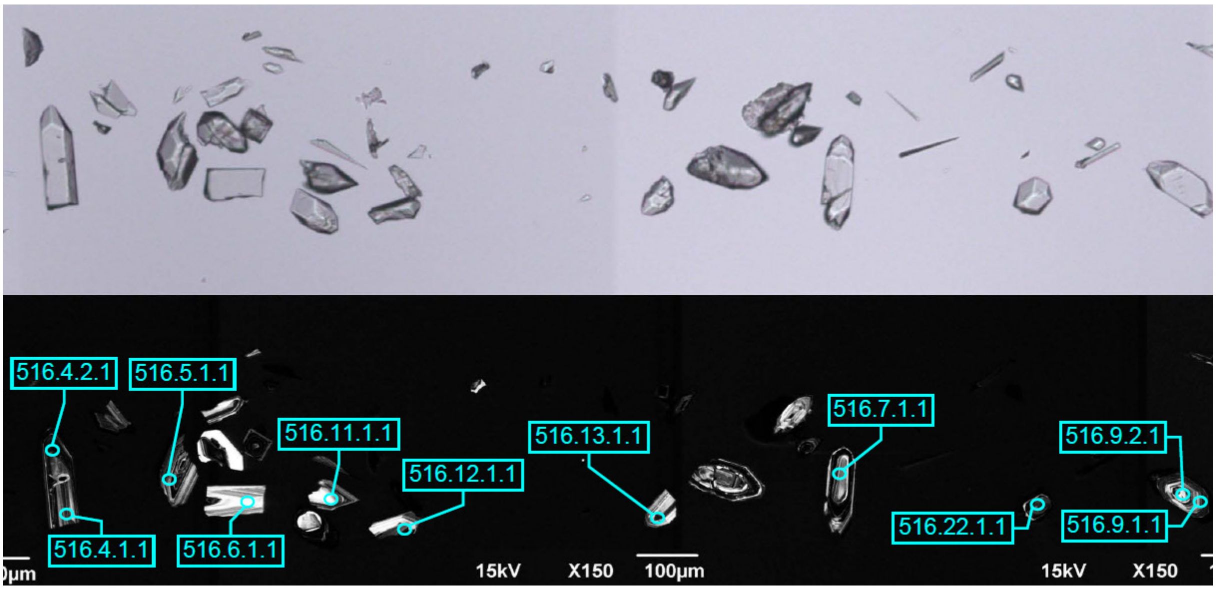


Figure 6.2 Representative zircons of the ‘Cuttaburra granite’ (GSNSW: PB-11-THOM-01, GA: 2128516). Transmitted light image is shown in the upper half and cathodoluminescence image in the lower half. SHRIMP analysis sites are labelled with sample (prefix 2128- not annotated), grain, spot and replicate number. Scale bar is 100 µm.

6.4 U–Pb Isotopic Results

Twenty-three analyses were obtained from 21 zircons; results are presented in Figure 6.3 and Table 6.2. The analysed zircons are characterised by a low to moderate range of ^{238}U contents (97–926 ppm, median 347 ppm), with moderate $^{232}Th/^{238}U$ (0.37–1.18, median 0.77) and low $^{206}Pb_c$ (maximum 0.19%, median 0.01%).

The 23 analyses can be divided into three groups:

- Group 1: 19 analyses (Figure 6.3, yellow fill) on concentric rims, grains with length-parallel banding and interiors of coreless grains yielded individual $^{206}Pb/^{238}U$ ages between ~437 Ma and ~414 Ma. The analyses combine to produce a weighted mean $^{206}Pb/^{238}U$ age of 428.3 ± 2.8 Ma (95% confidence, MSWD = 1.49, probability of equivalence = 0.08).
- Group 2: two analyses of grain cores with individual $^{206}Pb/^{238}U$ ages ~808 Ma and ~511 Ma (Figure 6.3, purple fill).
- Group 3: two analyses of grain cores with individual $^{207}Pb/^{206}Pb$ ages of ~2646 Ma, ~1419 Ma (Figure 6.3, green fill).

6.5 Geochronological Interpretation

The weighted mean $^{206}Pb/^{238}U$ age of 428.3 ± 2.8 Ma for the 19 analyses in Group 1 is interpreted to be the magmatic crystallisation age of the 'Cuttaburra granite'.

The four analyses in Groups 2 and 3 combined are interpreted as inheritance of Cambrian to Paleoproterozoic age.

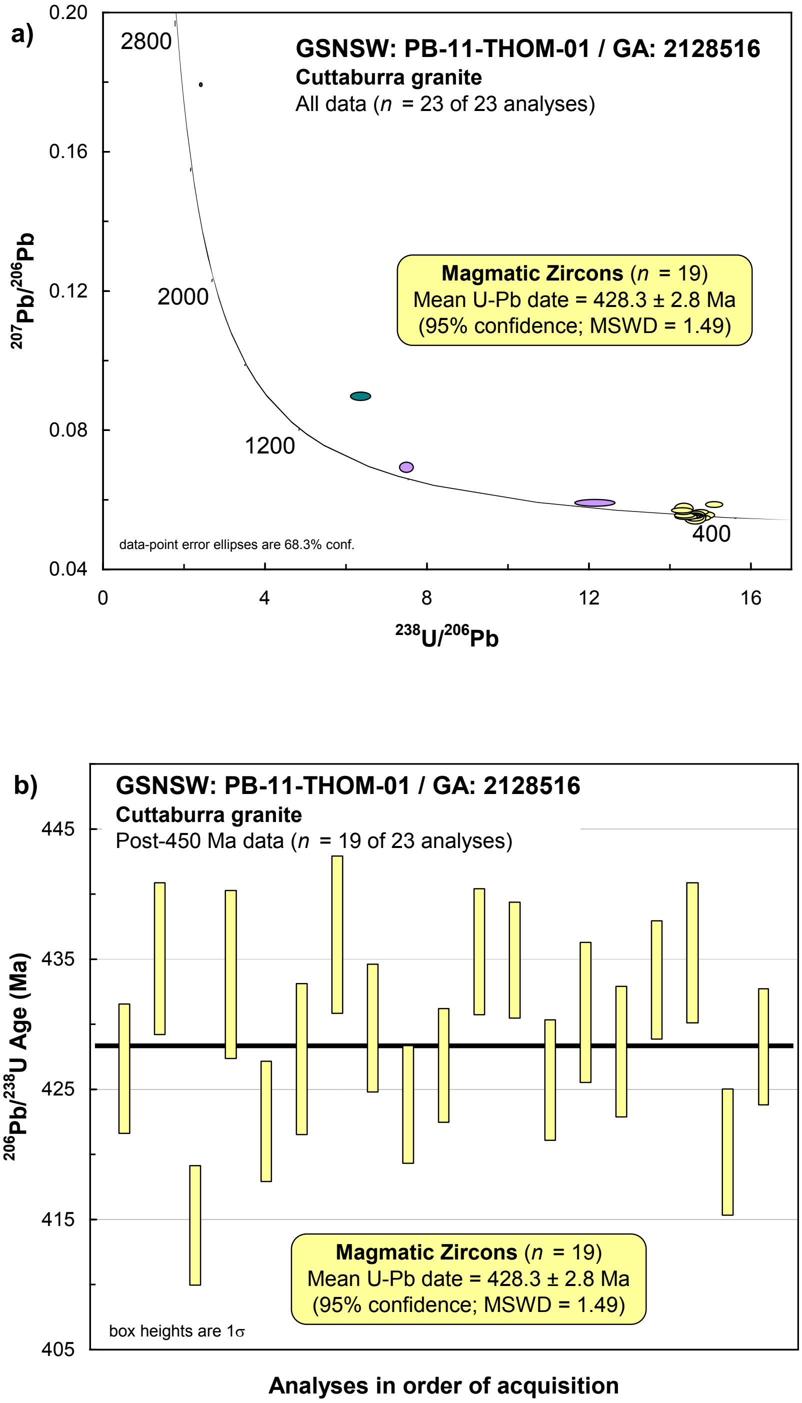


Figure 6.3 SHRIMP U–Pb data for zircons from the 'Cuttaburra granite' (GSNSW: PB-11-THOM-01, GA: 2128516). Yellow fill denotes magmatic population, purple fill denotes Cambrian–Neoproterozoic inheritance (Group 2), and green fill denotes pre–Neoproterozoic inheritance. (a) Tera-Wasserberg Concordia diagram; (b) Post ~450 Ma $^{206}Pb/^{238}U$ ages in order of acquisition; heavy black line represents the weighted mean $^{206}Pb/^{238}U$ age of the magmatic population.

Table 6.2 SHRIMP U–Pb isotopic data for zircons from the 'Cuttaburra granite' (GSNSW: PB-11-THOM-01, GA: 2128516). All ages are $^{206}Pb/^{238}U$.

Sample. Grain. Spot. Replicate	$^{206}Pb_c$ (%)	U (ppm)	Th (ppm)	$^{232}Th/^{238}U$	$^{238}U/^{206}Pb$	±1σ (%)	$^{207}Pb/^{206}Pb$	±1σ (%)	Disc. (%)	Age (Ma)	±1σ (Ma)
Group 1: Magmatic zircons (n = 19)											
2128516.3.1.1	-0.02	279	239	0.89	15.058	1.1	0.05862	1.1	26	414.5	4.6
2128516.12.1.1	-0.06	224	130	0.60	14.850	1.2	0.05564	1.5	4	420.1	4.9
2128516.5.1.1	0.07	371	415	1.15	14.764	1.1	0.05485	1.1	-4	422.5	4.6
2128516.10.1.1	0.07	456	404	0.91	14.717	1.1	0.05646	1.0	10	423.8	4.5
2128516.16.1.1	0.06	396	297	0.77	14.649	1.1	0.05529	1.1	0	425.7	4.6
2128516.1.1.1	-0.11	199	213	1.10	14.619	1.2	0.05575	1.5	4	426.5	5.0
2128516.19.1.1	-0.01	926	593	0.66	14.610	1.1	0.05547	0.7	1	426.8	4.4
2128516.6.1.1	0.13	97	84	0.89	14.592	1.4	0.05467	2.4	-7	427.3	5.8
2128516.18.1.1	0.09	216	132	0.63	14.573	1.2	0.05487	1.5	-5	427.8	5.0
2128516.20.1.1	0.05	738	486	0.68	14.559	1.1	0.05526	0.8	-1	428.2	4.5
2128516.13.1.1	<0.01	300	297	1.02	14.508	1.2	0.05538	1.1	-1	429.7	4.9
2128516.17.1.1	<0.01	381	344	0.93	14.467	1.3	0.05512	1.0	-3	430.9	5.4
2128516.4.2.1	0.01	628	545	0.90	14.380	1.1	0.05485	0.8	-7	433.4	4.5
2128516.4.1.1	0.06	297	339	1.18	14.366	1.5	0.05513	1.2	-4	433.8	6.5
2128516.15.1.1	0.02	888	314	0.37	14.329	1.1	0.05565	0.6	1	434.9	4.5
2128516.2.1.1	0.03	347	257	0.76	14.324	1.4	0.05546	1.0	-1	435.0	5.8
2128516.11.1.1	-0.27	149	110	0.76	14.309	1.3	0.05748	2.2	15	435.5	5.4
2128516.14.1.1	0.04	302	287	0.98	14.306	1.1	0.05649	1.2	8	435.6	4.8
2128516.9.1.1	-0.06	372	294	0.81	14.262	1.4	0.05690	1.1	11	436.9	6.1
Group 2: Cambrian–Neoproterozoic inheritance (n = 2)											
2128516.21.1.1	0.19	307	129	0.43	12.123	3.3	0.05913	1.3	11	511.0	16.1
2128516.7.1.1	0.01	356	152	0.44	7.492	1.9	0.06929	1.7	12	807.6	14.3
Group 3: Pre-Neoproterozoic inheritance (n = 2; $^{207}Pb/^{206}Pb$ age tabulated)											
2128516.9.2.1	-0.01	295	147	0.51	6.359	3.0	0.08968	1.1	36	1419	21
2128516.22.1.1	-0.01	524	236	0.47	2.432	1.1	0.17928	0.2	19	2646	4

Acknowledgements

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Appendix A Analytical Procedures

A.1 Summary

All isotopic analyses reported in this record were undertaken using the SHRIMP-IIe at Geoscience Australia in Canberra. A summary of key parameters from the analytical session is shown in Appendix Table A.1. The analytical procedures adopted (outlined in sections A.3–A.4) for zircon follow those published by Compston et al. (1984), Williams and Claesson (1987), Claoué-Long et al. (1995), Nelson (1997), and Williams (1998). Procedures and parameters relevant to the GSNSW–GA Geochronology Project are detailed in previous Records (e.g. Bodorkos et al., 2010, 2013), and parameters specific to this Record are updated below.

A.2 Sample Preparation

A.2.1 Sample Acquisition

The locations of field sites refer to the Geocentric Datum of Australia 1994 (GDA94). Coordinates are reported as decimal latitude and longitude, and as Map Grid of Australia eastings and northings (MGA94; Zone 55). Site locations are labelled using relevant identifiers in corporate databases: SITES SiteID for GSNSW, FIELDSITES SampleNo for GA.

The five samples in this record were received at Geoscience Australia as half and quarter diamond drill core (four samples), and hole-collared rockchips (Thule Granite) with weights between 0.9–25 kg.

A.2.2 Mineral Separation

In the Mineral Separation Laboratory at GA, whole rock samples were split into 4–6 cm blocks using a pre-cleaned Rocklabs hydraulic splitter, washed in an ultrasonic bath and dried in a Labec oven. Samples were then crushed to ~1 cm chips; approximately 50 g of sample was removed and set aside for geochemical analysis; the remaining sample was milled with a target grain size between 50 and 200 μm.

Mineral-density separation commenced with gravity separation on a Wilfley Table with multiple iterations resulting in sample reduction to ~1% of total sample weight. After drying the sample in a clean oven, a ferrous and a rare-earth magnet were used respectively to remove the paramagnetic grains from the heavy mineral fraction remaining from the Wilfley separation. The lesser-magnetic remnant then underwent a series of magnetic separations on a Frantz Isodynamic Separator (Frantz), with up to 12 separations in total. The magnetic current was sequentially increased, consecutively removing the more paramagnetic grains. The sample underwent density separation using Di-iodomethane (specific gravity 3.3) before being returned to the Frantz; sequential adjustments made to the horizontal tilt of the chute consecutively refined paramagnetic fractions. Zircon grains were then handpicked in a Petri dish in a solution of 99.95% ethanol. Selection of grains for all samples was biased towards the least magnetic and clearest grains to aid determination of a magmatic crystallisation age.

Appendix Table A.1 Summary of session-specific metadata for Session 120014, GA6192; parameters obtained from analyses of $^{206}Pb/^{238}U$ and $^{207}Pb/^{206}Pb$ reference zircons and samples analysed.

	Session 120014
MountID	GA6192
Session dates	13–16 February 2012
Calibration batch number	1 of 1
$^{206}Pb/^{238}U$ reference zircon	TEMORA2: 416.8 ± 1.3 Ma (Black et al., 2004)
Analyses used	33 of 33
$^{206}Pb/^{238}U$ session-to-session error (2σ)	0.36%
$^{206}Pb/^{238}U$ spot-to-spot error (2σ)	1.20% [increased to 2.00%]
Slope of ln($^{206}Pb+/^{238}U+$) / ln($^{254}UO^+/^{238}U^+$) [Calibration exponent C used, eqn (3)]	1.68 +0.28/-0.38 [2.00]
Mean $^{207}Pb/^{206}Pb$ age (Ma, 95% confidence)	448 ± 29 Ma
Mean ^{204}Pb overcounts/second from ^{207}Pb (95% confidence)	-0.020 ± 0.016 (no correction)
$^{207}Pb/^{206}Pb$ reference zircon	OG1: 3465.4 ± 0.6 Ma (Stern et al., 2009)
Analyses Used	18 of 18
Mean $^{207}Pb/^{206}Pb$ age (Ma, 95% confidence)	3466.5 ± 1.9 Ma
Mass fractionation correction applied	No
Number of Samples analysed	5
Unit Name / GSNSW SiteID (GA SampleNo)	Mount Halfway Volcanics / PB-11-NYM-15 (2128512)
Unit Name / GSNSW SiteID (GA SampleNo)	R7 Prospect, unnamed granite / PB-11-NYM-16 (2128513)
Unit Name / GSNSW SiteID (GA SampleNo)	Thule Granite / PB-11-NYM-17 (2128514)
Unit Name / GSNSW SiteID (GA SampleNo)	De Nardi Prospect, unnamed granite / PB-11-NYM-18 (2128515)
Unit Name / GSNSW SiteID (GA SampleNo)	‘Cuttaburra granite’ / PB-11-THOM-01 (2128516)

A.2.3 Mount Preparation

Where available, up to 200 handpicked grains for each of the five samples were mounted in a 25 mm epoxy-resin disc (mount GA6192) together with ~90 grains of the $^{206}Pb/^{238}U$ zircon reference TEMORA2 (416.8 ± 0.3 Ma, Black et al., 2004), ~85 grains of the $^{207}Pb/^{206}Pb$ OG1 zircon reference (3465.4 ± 0.6 Ma; Stern et al., 2009) and a fragment of the uranium concentration standard M257 (561.3 ± 0.3 Ma, 840 ppm U; Nasdala et al., 2008). After cooling, the mount was placed in an oven at 60°C for 24 hours to assist epoxy curing. Following curing, the mount was polished on a Struers polisher to expose an equatorial cross-section through the mounted zircon grains, photographed in reflected and transmitted light using a Leica DM6000 with a mounted Leica DFC310 FX 1.3 Mp camera, cleaned with ethanol and Milli-Q water and coated with a 2 nm coat of gold prior to cathodoluminescence imaging in a JEOL JSM-6490LV Scanning Electron Microscope housed at Geoscience Australia. The thin gold coat was then removed using 99.95% ethanol and the mount cleaned ultrasonically using first RB32 detergent, then petroleum spirit, followed by 99.95% ethanol and finally triple rinsed in Milli-Q water. The mount was dried in a 30°C oven prior to being coated with 15 nm of 99.999% gold.

The mount was loaded into the high-vacuum SHRIMP sample lock chamber 48 hours prior to analysis to enable complete out-gassing of the newly-cured epoxy and lowered into the SHRIMP source chamber immediately prior to analysis.

A.3 Zircon data acquisition and processing

A.3.1 Data Acquisition

Sensitive High Resolution Ion MicroProbe (SHRIMP) U–Pb zircon analyses were obtained on the SHRIMP-IIe instrument housed at Geoscience Australia.

A 70 µm Kohler aperture was used to achieve a 20 µm diameter primary beam of O_2^- ions at 10 keV (selected by means of a Wein filter) with total ion count at the mount surface between 1.5 and 2.5 nA to cause atoms on the crystal surface to sputter and ionise. Approximately 3 ng of sample is sputtered, forming a flat-bottomed pit 0.5–2 µm deep. Sputtered secondary ions are extracted from the sample surface and are focussed and steered through an electrostatic analyser and magnet into a collector through a series of electrostatic lenses and steering plates.

Prior to each analysis the surface of the analysis site was cleaned by rastering the beam for 3 minutes to reduce the amount of surface common lead. Data acquisition involved 6 magnet cycles through a ten mass-station run-table with the following counting times in seconds (s): $^{196}Zr_2O$ (2 s), background 204.1 (20 s), ^{204}Pb (20 s), ^{206}Pb (15 s), ^{207}Pb (40 s), ^{208}Pb (5 s), ^{238}U (5 s), ^{248}ThO (2 s), ^{254}UO (2 s) and $^{270}UO_2$ (2 s). A full analysis (six scans of the run-table) was set for 25 minutes with these conditions.

Once the instrument was tuned the analytical session commenced with an analysis of M257 zircon for calibration of the uranium concentration measurement (840 ppm; Nasdala et al., 2008) and data program inputs for SHRIMP software. This was followed by reference zircon analyses for an early indication of machine performance: $^{206}Pb/^{238}U$ ratios were calibrated using the TEMORA-2 reference zircon ($^{206}Pb/^{238}U$ = 416.8 Ma, Black et al., 2004), and $^{207}Pb/^{206}Pb$ ratios monitored using the OG1 reference zircon ($^{207}Pb/^{206}Pb$ = 3465.4 Ma, Stern et al., 2009).

Standard procedures in the GA Geochronology Laboratory for analysis site labels are used herein and take the form: SampleNumber.GrainNumber.SpotNumber.ReplicateNumber; where grains are numbered in sequence of analysis, spots are numbered in sequence of analysis within a grain, and replicates are numbered in sequence of analysis within a single spot location (e.g. 2128512.10.1.1).

Analyses were collected in a ‘round-robin’ sequence of one measurement from each igneous sample on the mount in turn with one measurement of TEMORA2 reference zircon made after every third sample analysis, and a minimum of one OG1 reference zircon measured after every second TEMORA2 measurement. Over the course of the session periodic data reduction was undertaken to monitor machine performance and assess the $^{206}Pb/^{238}U$ calibration and $^{207}Pb/^{206}Pb$ ratios.

A.3.2 Data Processing

Data from the SHRIMP was processed, calculated and portrayed using Microsoft Excel® 2003, and the add-ins SQUID 2.50.09.08.06 (Ludwig, 2009) and Isoplot v3.71.09.05.23 (May 2009 revision of Ludwig, 2003) downloaded from Sourceforge (http://sourceforge.net/). SQUID processes standard and spot data for evaluation, calculates element concentrations and isotopic ratios required for age calculation, and propagates the uncertainties associated with the $^{206}Pb/^{238}U$ ages. The decay constants used are those of Jaffey et al. (1971), together with present-day $^{238}U/^{235}U$ = 137.88, following the recommendations of Steiger and Jäger (1977).

Common-Pb corrections for unknowns were based on measured ^{204}Pb, and a Pb isotopic composition calculated using the single-stage Pb isotopic evolution model of Stacey and Kramers (1975) at an age corresponding to the individually estimated age of each unknown analysis. The result of this calculation is expressed for each analysis in each of the analytical data-tables, in terms of common ^{206}Pb as a percentage of total measured ^{206}Pb. All isotopic ratios and ages cited in this Record are corrected for common Pb ($^{206}Pb_c$).

Ages derived from the pooling of multiple individual analyses are error-weighted means unless otherwise specified, and their uncertainties are quoted at the 95% confidence level unless otherwise indicated. Each error-weighted mean has an associated Mean Square of Weighted Deviates (MSWD) value, which is a measure of the degree of scatter of the constituent analyses relative to the assigned uncertainties (Ludwig, 2003), and a probability of equivalence value, which is the probability that all of the constituent analyses are equivalent within their uncertainties. By convention, scatter beyond the assigned uncertainties is assumed to be present when the probability of equivalence is less than 0.05.

A.3.3 Calibration Procedures

Elemental U concentrations in the unknown zircons were calibrated using the M257 reference zircon (840 ppm U; Nasdala et al., 2008), and the power-law relationship of Claoué-Long et al. (1995):

$$\left[{}^{196}Zr_2O^+/{}^{238}U^+\right] = A \times \left[{}^{254}UO^+/{}^{238}U^+\right]^{0.66} \tag{1}$$

where A is a session-dependent constant determined from measurements on M257. All U concentration data tabulated for unknowns have uncertainties of the order of 15–20%, based on the extent of known variations in U abundance in M257.

The values of $^{232}Th/^{238}U$ in the unknown zircons were calculated using the relationship proposed by Williams et al. (1996):

$$^{232}Th/^{238}U = \left[{}^{248}ThO^+/{}^{254}UO^+\right] \times \left\{\left(0.03446 \times \left[{}^{254}UO^+/{}^{238}U^+\right]\right) + 0.868\right\} \tag{2}$$

The values of $^{206}Pb/^{238}U$ in the unknowns were calibrated using the TEMORA2 reference zircon ($^{206}Pb/^{238}U$ = 0.0668, corresponding to an age of 416.8 Ma; Black et al., 2004), and a power-law relationship (Claoué-Long et al., 1995) of the form:

$$\left[{}^{206}Pb^+/{}^{238}U^+\right] = B \times \left[{}^{254}UO^+/{}^{238}U^+\right]^2 \tag{3}$$

where B is a session-dependent constant determined from measurements on TEMORA2.

The values of $^{207}Pb/^{206}Pb$ in the unknowns were monitored using the OG1 reference zircon ($^{207}Pb/^{206}Pb$ = 0.29907 ± 0.00011, corresponding to an age of 3465.4 ± 0.6 Ma; Stern et al., 2009). For each session, the error-weighted mean $^{207}Pb/^{206}Pb$ for OG1 (denoted $[^{207}Pb/^{206}Pb]_{OG1}$) was calculated (Appendix Table A.1); however, in the samples documented in this Record, zircons of pre-Neoproterozoic age were rarely encountered, and the calculation of weighted mean $^{207}Pb/^{206}Pb$ ages was unnecessary. Uncertainties on individual $^{207}Pb/^{206}Pb$ analyses are governed by (relatively poor) counting statistics, and are almost always large enough that both the instrumental mass fractionation correction and its associated uncertainty are rendered insignificant. Consequently, the tabulated values of $^{207}Pb/^{206}Pb$ for each sample have not been corrected for instrumental mass fractionation.

A.3.4 Propagation of Uncertainties

In each session, a 'calibration constant' value is determined for each individual analysis of the $^{206}Pb/^{238}U$ reference zircon TEMORA2 (i.e. $b_i = [^{206}Pb^+/^{238}U^+]_i/([^{254}UO^+/^{238}U^+]_i^2)$). Uncertainties associated with each of these individual 'calibration constants' (i.e. ± b_i) are governed primarily by the counting statistics associated with the constituent isotopic ratio(s). The value of the session 'calibration constant' (B; see equation (3)) is calculated as the error-weighted mean of the session-specific population of individual calibration constants. However, these populations commonly display significant excess scatter, manifested as an MSWD value for B that exceeds unity, despite the fact that most reference zircons are (by definition) characterised by $^{206}Pb/^{238}U$ homogeneity at a range of scales. This indicates that the values of ± b_i are usually underestimated in going from analysis to analysis. Consequently, for each session, SQUID calculates the constant additional uncertainty per spot (expressed as a percentage) that needs to be added in quadrature to each ± b_i value, in order to produce MSWD ~1 for the population of b_i values used to calculate B (Ludwig, 2009). This constant additional uncertainty is termed the external 'spot-to-spot error' (or 'reproducibility'), and its session-specific 2σ values are presented in Appendix Table A.1. The 1σ spot-to-spot error is added in quadrature to the other sources of error (principally related to counting statistics and the common Pb correction) for each value of $^{206}Pb/^{238}U$ in the unknowns, and thus is incorporated in the uncertainties for all individual $^{206}Pb/^{238}U$ values presented in the analytical data-tables.

For each session, SQUID also calculates an uncertainty for the session-specific calibration constant (i.e. ± B). This uncertainty is termed the 'session-to-session error' (or 'calibration uncertainty'), and its session-specific 2σ values are presented in Appendix Table A.1. The session-to-session error is not included in the uncertainties for individual $^{206}Pb/^{238}U$ values presented in the analytical data-tables, and should be neglected when comparing error-weighted mean $^{206}Pb/^{238}U$ ages for unknowns co-analysed in a single analytical session. However, it must be accounted for when seeking to compare $^{206}Pb/^{238}U$ datasets more widely (e.g. between different analytical sessions), especially when calculating error-weighted mean $^{206}Pb/^{238}U$ ages for unknowns, because the session-to-session error can be of comparable magnitude to the 95% confidence interval arising from population statistics.

For example, calculating the magmatic crystallisation age of the Thule Granite (GSNSW: PB-11-NYM-17, GA: 2128514) using the 28 $^{206}Pb/^{238}U$ ages in Group 1 (Table 4.2) yields a weighted mean age of 425.7 ± 1.9 Ma (i.e. an uncertainty of 0.38% at the 95% confidence level) based solely on the tabulated data. This uncertainty is appropriate for the purpose of direct comparison with the co-analysed granite at the R7 Prospect (GSNSW: PB-11-NYM-16, GA: 2128513), for which the analogous calculation yields a weighted mean $^{206}Pb/^{238}U$ age of 422.8 ± 4.6 Ma for the four analyses in Group 1 (Table 3.2), because the two samples were co-analysed and thus share a common calibration. However, when seeking to compare the magmatic crystallisation age of the Thule Granite with any other SHRIMP result, it is necessary to include (via quadratic addition) the session-to-session error for the relevant session (0.36% (2σ) for session 120014; Appendix Table A.1), and the expanded uncertainty is given by sqrt[$(0.38\%)^2 + (0.36\%)^2$] = 0.52%, which represents an absolute uncertainty of 2.4 Ma relative to a weighted mean of 425.7 Ma. Consequently, the magmatic crystallisation age of the Thule Granite is reported as 425.7 ± 2.4 Ma (and the unnamed granite from the R7 Prospect at 422.8 ± 4.9 Ma) throughout this Record, in order to maximise age comparability with existing (and future) geochronological determinations.

A.3.5 Discordance

Discordance is a measure of the internal agreement of the $^{207}Pb/^{206}Pb$ and $^{206}Pb/^{238}U$ ages derived from the independent $^{207}Pb/^{206}Pb$ ratio and ^{238}U–^{206}Pb isotopic system, within a single analysis. In zircons of Mesoproterozoic and older age, discordance values for single analyses (and discordance patterns within a population of analyses) can provide important information about the timing and extent of radiogenic Pb loss (see Sircombe et al. (2007) and Carson et al. (2010) for detailed discussions), and are often a valuable indicator of 'geological' data quality. The comparison is less useful in SHRIMP analyses of post-1000 Ma zircons, because the poor counting statistics associated with $^{207}Pb/^{206}Pb$ determinations in these young grains usually result in uncertainties large enough to obscure the 'true' agreement or otherwise of the two isotopic systems. Therefore, a comparison of discordance is not included in this record, but results for discordant values are presented in the tables for individual samples. Nevertheless, the comparison has been performed throughout this Record, using the equation:

$$\text{Disc (\%)} = 100 \times \left[\left({}^{207}\text{Pb}/{}^{206}\text{Pb date}\right) - \left({}^{206}\text{Pb}/{}^{238}\text{U date}\right)\right] / \left({}^{206}\text{Pb}/{}^{238}\text{U date}\right) \quad (4)$$

The analysis specific results of equation (4) are reported in each of the analytical data tables.

A.4 Session-specific calibrations and data processing

The data reported herein was obtained in a single analytical session. Session-specific calibrations and data processing are summarised in Appendix Table A.1 and detailed session-specific information is below.

A.4.1 Session 120014: Mount GA6192, 13–16 February 2012

This session comprised the analysis of five samples:

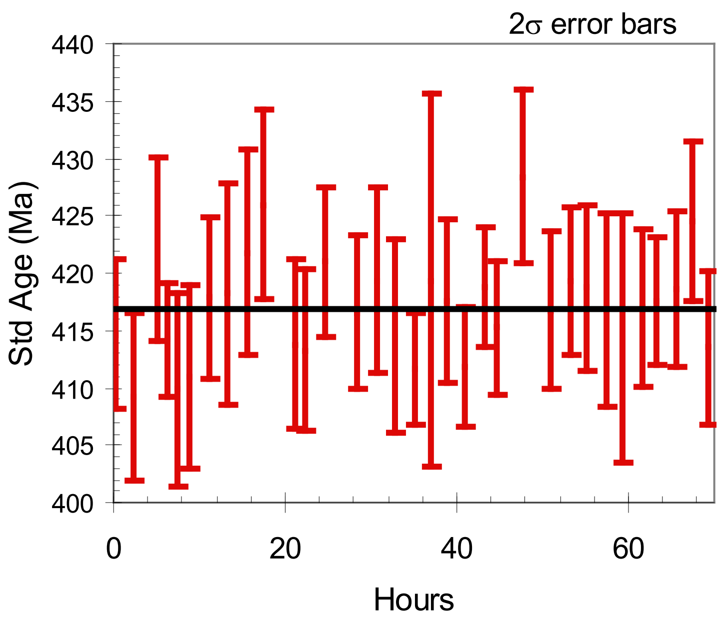
- GSNSW PB-11-NYM-15 (GA 2128512): Mount Halfway Volcanics
- GSNSW PB-11-NYM-16 (GA 2128513): unnamed granite at R7 Prospect
- GSNSW PB-11-NYM-17 (GA 2128514): Thule Granite
- GSNSW PB-11-NYM-18 (GA 2128515): unnamed granite at De Nardi Prospect
- GSNSW PB-11-THOM-01 (GA 2128516): 'Cuttaburra granite'

A total of 33 analyses of the TEMORA2 zircon standard were obtained during SHRIMP session 120014 at Geoscience Australia. Instrument operating conditions were predominantly stable, resulting in little variation of Ln [$(^{238}U^{16}O)^+/^{238}U^+$] for the 33 analyses, and the slope of the robust regression was 1.68 +0.28/-0.38. As the 95% confidence level, this value differs significantly from the canonical value of 2.00. Processing data with defined slopes did not alter the results; therefore, equation (3) was used with a value of 2.0 to define the calibration exponent B.

All 33 analyses were used to define the calibration (Appendix Figure A.1), with a 2σ session-to-session error of 0.36% and a 2σ spot-to-spot error of 1.20%. The session-to-session error is included, in quadrature, in the uncertainty of each weighted mean $^{206}Pb/^{238}U$ age calculated for this session. The spot-to-spot error, however, is lower than that typically determined for TEMORA2 on the GA SHRIMP IIe (eg: Appendix A.3.5 of Bodorkos et al., 2013), which raises the possibility that the value determined for session 120014 is underestimated. Consequently, the spot-to-spot error for session 120014 was increased to a nominal value of 2.00% (2σ) prior to its incorporation in quadrature into the uncertainties of individual $^{206}Pb/^{238}U$ analyses in the unknowns, based on (i) the recommendations of Stern and Amelin (2003) regarding the unaccounted variation in $^{206}Pb/^{238}U$ measurements via SHRIMP in general.

Overcounts on mass ^{204}Pb were monitored through reference to the robust mean of the $^{207}Pb/^{206}Pb$ ages determined for TEMORA2 (448 ± 29 Ma). This result is slightly older than the reference value (416.8 ± 0.38 Ma; Black et al., 2004) at the 95% confidence level indicating that ^{204}Pb was potentially incorrectly counted. Estimated ^{204}Pb undercounts based on measured ^{207}Pb are non-zero(-0.020 ± 0.015), but are not supported by ^{204}Pb undercounts based on measured ^{208}Pb, which are indistinguishable from zero (-0.006 ± 0.020), therefore no correction was applied.

A total of 18 analyses of the $^{207}Pb/^{206}Pb$ reference zircon OG1 were obtained over the SHRIMP session with a weighted mean of 3466.5 ± 1.9 Ma (MSWD = 0.88). As this result is indistinguishable from the OG1 reference value of 3465.4 ± 0.6 Ma (Stern et al., 2009), no correction for instrumental fractionation of $^{207}Pb/^{206}Pb$ was applied to the session.



Appendix Figure A.1 SHRIMP $^{206}Pb/^{238}U$ ages on TEMORA2 zircon during SHRIMP Session 120014 in order of acquisition. Heavy black line is the reference age of 416.8 Ma. Error bars are 2σ, n = 33.